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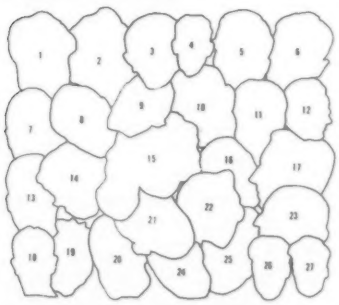

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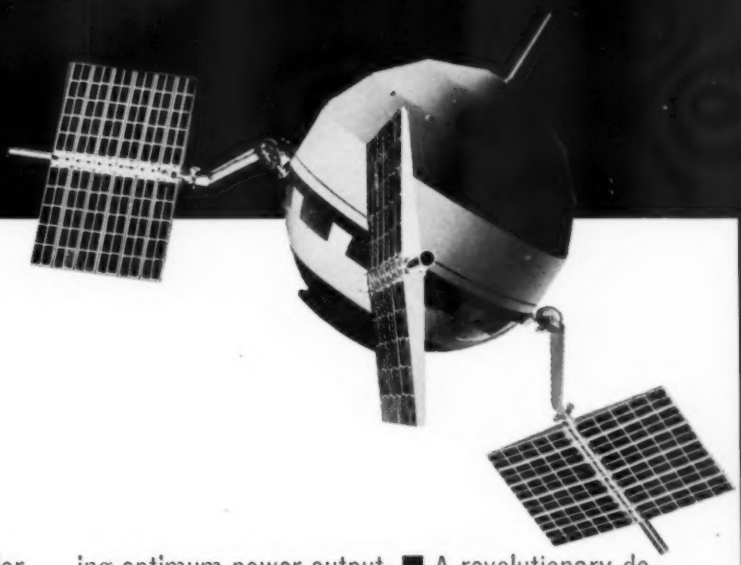

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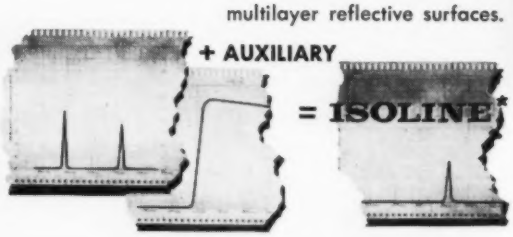

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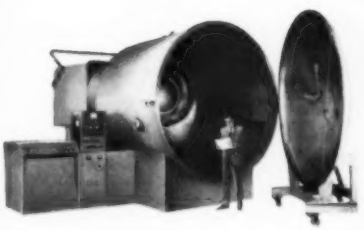

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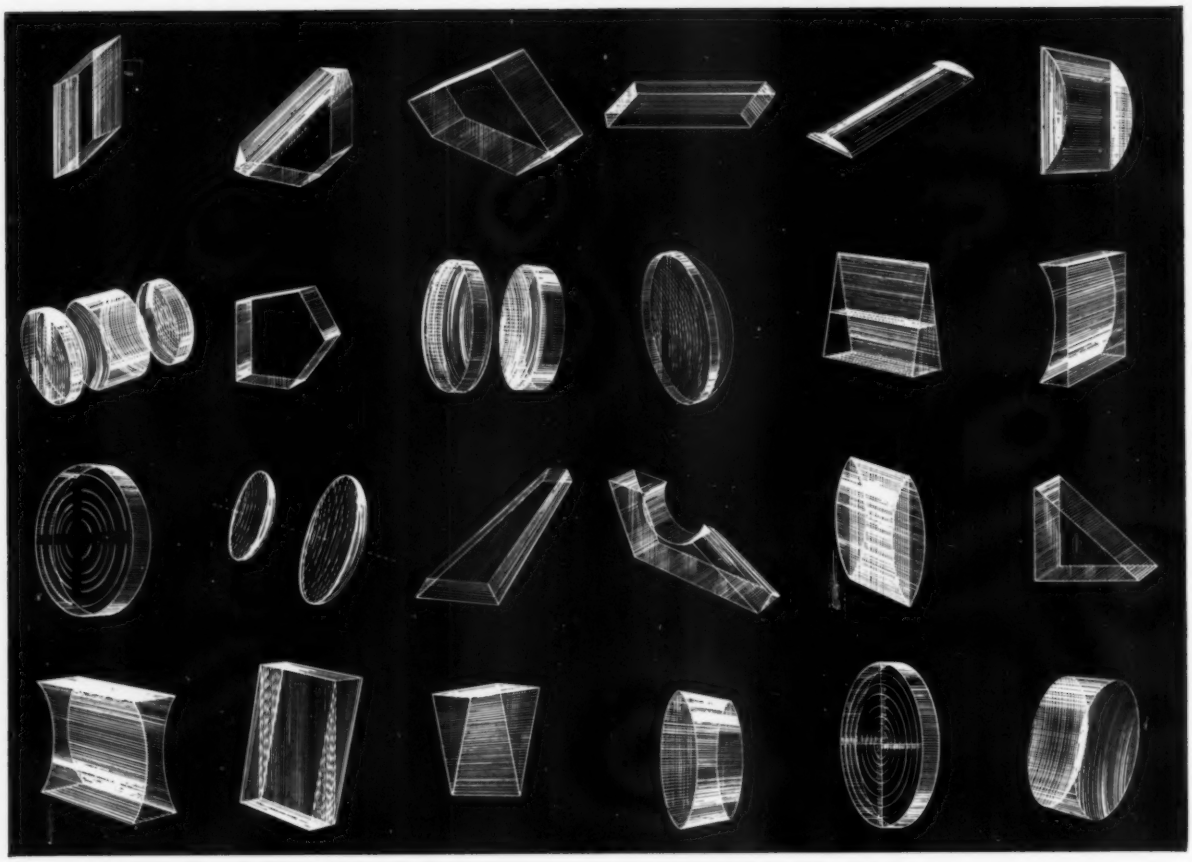

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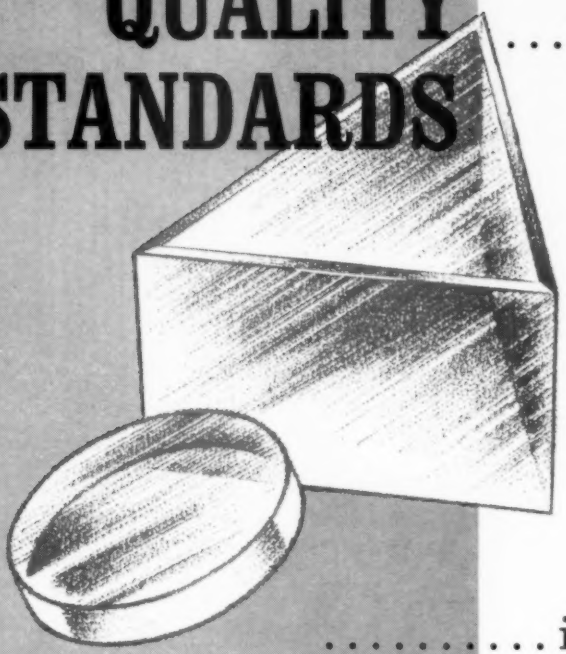

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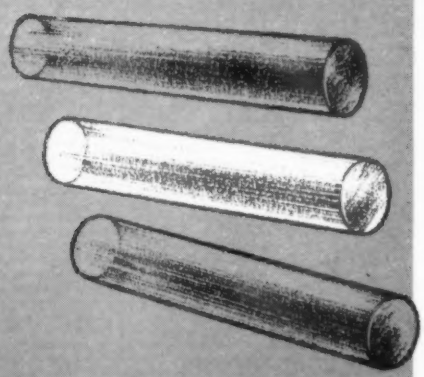

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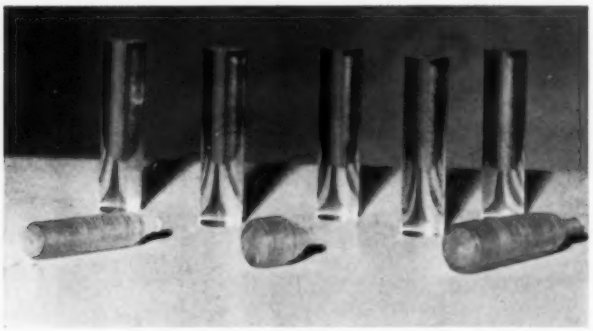

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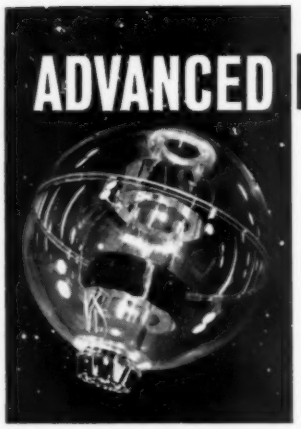

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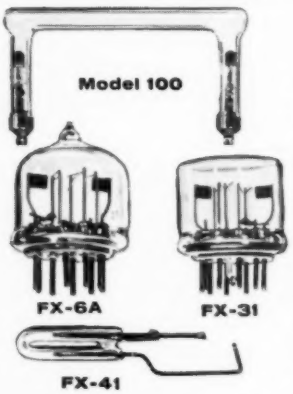

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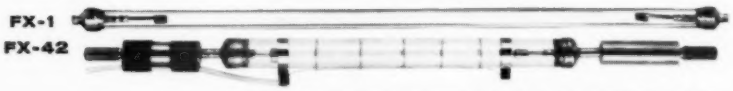

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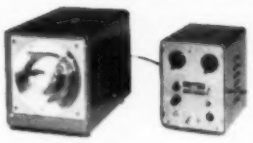

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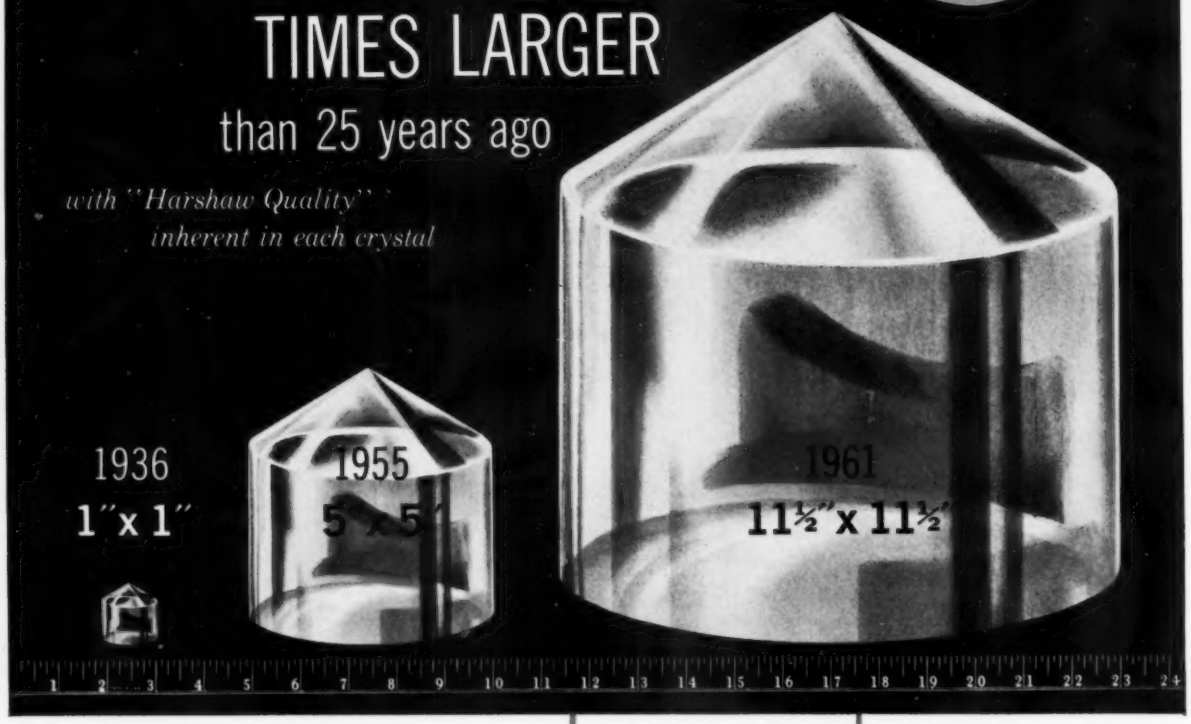

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Scientists and Engineers

Erik Ingelstam

In our generation, particularly since World War II, the scientist has been given a place in the sun. Instead of being isolated in his study and laboratory, an eccentric, learned, and therefore interesting person, albeit a necessary and harmless one, he has been found to be the keeper of the "prestige" of world powers, and he is "sought for in public counsel."

How has he attained this position? In the first place by his ability to produce a technical product. Nuclear physics was a branch of science of little interest to the average man and to engineers until the atomic bomb appeared on the scene; a new discovery such as the optical maser achieves its glamor because it can throw a beam of light to the moon. If we were to distinguish between a scientist and an engineer in the old meaning, we should arrive at the incongruous conclusion that it was not until the scientist became an engineer that he won general respect. But an old-time engineer, who, by his inventiveness or mechanical gifts made new machines work, had few gifts that attracted the appreciative attention of the circle of isolated scientists. It would not surprise me to learn that technical colleges and the like were despised in the ancient university cities of all countries. When, after taking my doctor's degree, I left the "fine" old Uppsala University to become a lecturer at an Institute of Technology, I am sure that many of the friends I left behind regarded it as a step downwards.

All that was changed during the 1940's. Technical research and the training of the new type of applied scientists grew in value, and now the universities of Sweden are literally clamoring to be allowed to provide the same kind of education as that given by the technical colleges and institutes.

I have here hinted at the spirit of mutual disdain often prevailing formerly between pure scientists and engineers, a conflict that still exists in somewhat altered forms. Lack of appreciation of exhaustive, basic, "useless" research is often revealed by the economically short-sighted engineer. There are leaders of industry who seem rather shy of Ph.D.'s, but favor people who struggle upwards as self-made men. And have not similar ideas emerged when associations and journals for applied science have been established, even though "science" has been considered a good selling term?

Still the branches have merged into each other logically. A story is told of how astonished the great closet-scholar Lord Rutherford was when he learned that apparatus for scientific research could be designed and then made by—an engineer. The head of an institution today sometimes feels only too well his dependency on makers and suppliers of the complicated equipment he and his co-workers need.

An engineer at a progressive industrial plant is now equally aware that academic research is the key to technical progress, mention of which is, in this era of the transistor and rocket fuel, rather superfluous. But still the situation is such a new one that we have not yet been able to free ourselves of emotional undervaluation, and our seats of learning in particular are in a difficult dilemma. They have not kept pace with development, and only in certain elements has an education really suitable for the combined scientist-engineer been evolved. The two objectives—the one to seek knowledge for its own sake and to satisfy the incurable curiosity of human beings, and the other to investigate in order to produce what humanity needs in the way of food, dwellings, communications, physical and spiritual—are far too seldom viewed together. I believe in the value of educational institutions of a wide range, naturally consisting of groups of specialists.

I would like to see industries, with their great resources, keep in touch with the universities and actively support their institutions financially and by supplying them with research problems. *Not* by making the professor into a highly remunerated consultant, but by providing tasks for him to take to his students or to the research workers who have chosen to remain in a university. I have good personal experience of a university

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institution with two sponsors: the State, which is responsible for basic research and higher education, and a group of industrial firms which makes generous annual grants—together totaling, perhaps, more than the State—to ensure that a staff of research workers will be available when needed. In other words, they contribute towards the important task of training research workers and enable them to accumulate a greater fund of knowledge, before they are assigned specific tasks. This type of organization cannot always be realized, but industry, which is so eager to engage every one of our pupils, should accept part of the responsibility for the training of groups of young research workers in a relatively wide sphere in the receptive and creative years during which they are working for their Ph.D. degrees.

An institute, however, has duties to perform with respect to both basic science and the engineering section of the science. It must not become an establishment handicapped by contract jobs that have to be concluded and reported as quickly as possible. The main task of the leader or leaders of the group is, perhaps, to find out what tasks are most suitable for a young scientist. If he wishes to devote himself to theoretical work he must be assisted in finding contracts that will help him to further his development—even though industrial tasks may be completely lacking. This is a sound view also because, as someone has said, there is seldom anything so unpractical that it cannot be used in some way or other in the future. If he wishes to experiment—far too few students seem willing nowadays to sacrifice the long time this usually demands—he experiences in the first years of his activities the necessary coordination between the theoretical considerations and the control over the recalcitrant material required to make an experiment successful.

I do not mean to imply that it is of importance where the work is performed. It may be at the university, in an independent research institute, or in the research department of an industrial plant. But it is of great importance that basic research flourish, even though it does not yield an immediate profit, and that the people required to solve the technical problems of tomorrow be given a thorough training. It would be a mistake to think that a practical problem will not further the progress of basic research. It has often done so when an inventor has had the bright idea of making use of some physical law, and new features of this law have been revealed. It is our task as experimentalists to develop methods which will result in experiments functioning in the way we hoped they would, which means that much of what we call free research is aimed at definite objectives. We are even happier if the experiment reveals something we had not expected.

C. P. Snow has written about the two separate cultures—that of the literary intellectuals and that of the scientists. We should also pay attention to the subcultures, which are so summarily called pure and applied science, the relations between which must certainly be improved. It is to be hoped that the readers of *Applied Optics* and the *Journal of the Optical Society of America* will be largely the same people, or that they, by numerous cross references, will be taught that applied implies pure, and that we cannot in the development of our science dispense with the science of engineering.

Opening Session July 1961 ICO London Meeting: A. C. S. Van Heel *Netherlands*, G. C. Ottway *SIMA*, P. Mollet *Belgium*, P. M. S. Blackett *Imperial College*, E. W. Taylor *Chairman, British National Committee for Optics*, Erik Ingelstam *President of the ICO*, Sir Patrick Linstead *Rector of Imperial College*, A. Maréchal *Paris*, P. Fleury *Paris*, G. Toraldo di Francia *Italy*, Stanley S. Ballard *Past President ICO*, and W. D. Wright *Imperial College*.

Optics in Sweden

Yngve Öhman

Scientific Research during the 18th and 19th Centuries and the Beginning of the 20th Century

Optics has old traditions in Sweden. During the 18th century an important contribution to geometrical optics was made by S. Klingenstierna (1698–1765), Professor of Physics and Mathematics at the University of Uppsala. In a paper published in 1754 in Volume XV of the *Transactions* (*Handlingar*) of the Royal Swedish Academy of Sciences he presented theoretical considerations of great value for the true understanding of the law of refraction. The views expressed there differ from those of Newton, and they initiated therefore an interesting scientific discussion. Dollond, in his early constructions of achromatic telescopes, was considerably stimulated by this discussion. The appearance of two later papers (1760 and 1762) on chromatic and aplanatic lenses led to considerable progress in the design and manufacture of lenses. Therefore, Klingenstierna may be said to have contributed in a valuable way to the invention of the achromatic telescope.[1]

During the 19th century several Swedish names were connected with pioneering work in optics. The work carried out in Uppsala by A. J. Ångström (1814–1874) has been considered of such fundamental importance to optics that his name was honored in the selection of the spectroscopic unit of wavelength. Another Swedish pioneer in spectroscopy was J. R. Rydberg (1854–1919), Professor of Physics at the University of Lund. His name, too, is familiar to most students of physics by the "Rydberg constant."

An important contribution in radiation-measuring techniques was made in 1851 by A. F. Svanberg (1806–1857), Professor of Physics in Uppsala. He was the first to suggest the bolometer principle, developed later by Langley into a high sensitivity measuring device. Important radiation-measuring instruments were developed also by K. J. Ångström (1857–1910), the son of A. J. Ångström. In fact his pyrheliometer of 1896 is still considered one of the best instruments when measuring the solar constant of radiation.

At the end of the 19th century and the beginning of the 20th, geometrical optics had a prominent representative in Sweden in A. Gullstrand (1862–1930). Though originally a professor of ophthalmology he devoted much of his time to mathematics and made a series of important contributions to the mathematical theory of aberrations including those of high order. He also worked on systems without a common axis, and showed that the eye itself sometimes constitutes such a system. In fact he presented very complete data on all the aberrations of the eye, including effects produced by the motion of the eye itself.

Gullstrand was able to make a very complete exploration of the general laws of image-forming systems and arrived at results of great practical use. A most fruitful collaboration was established with Carl Zeiss in Jena ("Die Gullstrandschen Stargläser mit asphärischen Flächen," "Das grosse Gullstrandsche Ophthalmoskop," "Monokulares Handophthalmoskop nach Gullstrand," etc.).

Gullstrand was awarded the Nobel Prize for medicine in 1911 for his achievements in ophthalmology, and in 1914 he was awarded a personal professorship at the University of Uppsala in physiological and physical optics.

The mathematical treatment in Gullstrand's papers is sometimes laborious and difficult to follow owing to a strictly geometrical procedure. As expressed by Born[2]: "It is to be admired that Gullstrand was able to establish in this way fundamental laws of general validity." By considering instead the characteristic function (Brun's Eikonal of 1895 etc.) M. Herzberger and others have later given a somewhat more apt description of some of the results achieved by Gullstrand. According to Born[2] it seems that Gullstrand did not have full confidence in this method of approach in the case of systems without a common axis (see also ref. 3).

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Recent Work and Current Research

A considerable part of the optical research in Sweden during the present century has some direct or indirect connection with the name of Manne Siegbahn. Professor Siegbahn received the Nobel Prize for physics in 1925 for his spectroscopic discoveries and studies of x-ray phenomena. Among important contributions made by Siegbahn in the field of optics may be mentioned the design of excellent grating-ruling machines. His interest in ruling gratings originated in about 1919, when he succeeded Rydberg as Professor of Physics at the University of Lund. The first machine he designed was completed shortly after he had moved to the University of Uppsala in 1923. His gratings were intended first for x-ray analysis, but with the creation in 1937 of the "Forskningsinstitutet för Fysik" in Stockholm he could soon supply Swedish optical research and also foreign research centers with high quality gratings.

In this field most valuable contributions have also been made by E. Hulthén, Professor of Physics at the University of Stockholm, who has tried recently, with much success, the principle of repeated reflections for the purpose of increasing the resolving power of gratings. For similar purposes he has made promising experiments with "refraction gratings."

Important contributions to ultraviolet spectroscopy technique have been made at Uppsala and Lund by B. Edlén. Among contributions in the field of spectroscopic design should be mentioned also the work carried out by H. Lundegårdh at Ultuna, Uppsala.

At "Forskningsinstitutet för Fysik" and at the Geographical Survey Office in Stockholm Erik Bergstrand has developed a new and very accurate method of determining the velocity of light. The method has found valuable practical application in the construction of a "geodimeter" for geodetic field work.

An event which, during the last ten years, has meant considerable development of optical research in Sweden was the creation of The Institute of Optical Research. Already in 1948 a proposal had been made by M. Siegbahn, through the Swedish Natural Science Research Council and the Swedish Council of Technical Research, that an Institute of Optics should be established at the Royal Institute of Technology in Stockholm. Such an institute had *de facto* been in operation since 1950, with E. Ingelstam as director of research. But it was not until 1955 that the Government guaranteed the permanent character of this institution. According to present rules some members of the council are nominated by the Government and some by a special committee representing Swedish optical industries and other institutions.

Though only slightly more than ten years have elapsed since optical research was started at the institute, a considerable number of investigations have already been completed there by Ingelstam and his collaborators (O. Bryngdahl, E. Djurle, L. O. Hendeberg, P. Hjelmström, L. Huldt, L. Johansson-Sjöfall, P. Lindberg, and others). Important scientific contributions with practical applications have been made, especially in the field of phase contrast technique, and in the design of improved refractometers and interference microscopes. Valuable contributions to modern progress in the field of optical image transfer have also been presented, and the first European apparatus for the measurement of transfer functions was designed at the Institute as long ago as 1951. Several important papers have been devoted to the optical properties of semiconductors (Huldt) etc., and a group is doing research in the field of evaporated thin films for use in optics.

The Institute has more and more become the Swedish center of optics with intimate connections with corresponding institutions abroad. In 1959 the International Commission of Optics held a conference there, and on this occasion Ingelstam was nominated President of the ICO. He had been Vice-President of the same Commission and for many years the executive secretary of its Swedish national committee.

Among scientific institutions in Sweden where applied optical research is being carried on, mention should also be made of the institutions for geodetic sciences and for photography at the Royal Institute of Technology, the Research Institute of National Defence (high-speed photography, infrared detectors etc.), and the institution for teletechnics (H. Wallman) at Chalmers Technical University in Gothenburg. Special optical design has been made in connection with some of the chemical and medical institutions and in several other centers of research.

Finally, reference should be made to the astronomical institutions in Sweden. B. Lindblad, director of the Stockholm Observatory in Saltsjöbaden (who once upon a time worked in Gullstrand's calculating bureau in Uppsala), has always been interested in Swedish optical design, and has taken an active part in the creation of the Swedish Institute of Optics. At the Observatory he has erected an optical workshop for grinding and aluminizing. Several Swedish institutions have had large mirrors and plates coated here. This work has been performed under the supervision of J. Ramberg who has taken an active part in the design of new instruments for the Observatory. He is a member of the special instrument commission working out plans for the European observatory in the southern hemisphere. Various kinds of auxiliary optical instruments have been designed at the Stockholm Observatory by the present writer, such as the birefringent filter (independent of, though somewhat later than, Lyot), polarigraphs, a photoelectric colorimeter, visual photometers in solar

research (in use at the Swedish solar observatory in Anacapri), and thermomagnetic radiation measuring device using gadolinium, etc.

At the astronomical observatory in Uppsala an optical workshop was erected by the former director, G. Malmquist, and optical grinding and aluminizing of large mirrors has been performed there under the supervision of Å. Wallenquist in connection with the installation of a large Schmidt telescope at Kvistaberg.

Important constructions of photoelectric devices for different purposes have been made at the astronomical observatory in Lund, in collaboration with the Physical Institute.

Optical Industries in Sweden

Though glass-making has old traditions in Sweden, it was not until this century that large-scale production of optical products began. The first manufacture of optical products is connected with the name of G. Dalén, the Swedish inventor who was awarded the Nobel prize for physics in 1912 for his automatic lightsensitive shutter for lighthouses. Dalén became President of AB Gasaccumulator (AGA) in 1909, and since about that year lenses and prisms have been manufactured on a large scale by this company.

A new and much more important period of development in Swedish optical manufacturing started during World War II. Three different companies—Aga, Jungnerbolaget, and AB G. Arehn—made great investments for the purpose of producing optical products of the highest possible quality on a large scale. Of these companies Aga and Jungner are still working in this area with a good capacity. In the Aga company the late E. Aulin was for many years the scientific authority on problems related to optics. With great generosity he offered his services not only to his own company but also gave much valuable help and advice to many Swedish scientific institutions. In this way he should be given considerable credit for much of the progress made in Swedish optics during the last two decades.

The Jungnerbolaget has also been fortunate in having at their disposal very able specialists in optical design, and has sveceeded in manufacturing products of very high precision.

Another company which has meant much to Swedish optics during the last decades is the Lumalampan AB. The research department of this company has offered its services to many of the scientific institutions of Sweden.

All the three companies, Aga, Jungner, and Luma, have intimate connections with the Institute of Optics in Stockholm and have given support to the activities of this institute.

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VIENNA WMO AUGUST 1961

Professor Ångstrom *Stockholm* and friends including D. Q. Wark *Washington DC* and W. Morikofer *Davos* during a convivial interlude in Vienna

More bon vivants in Vienna August 1961 including F. Steinhauser *Vienna*, Dr. and Mrs. H.J. Bolle *Munich*, Mrs. Morikofer *Davos*, S.D. Smith *Reading*, and C.D. Rodgers *Cambridge University*

See page 379 for report.

Optics in Canada

K. M. Baird

Optics in Canada has not been characterized by a long tradition in the optical industry and has therefore lacked much of the kind of research and development usually associated with an optical industry. However, while economic considerations tend to rule against the large scale development of an optical industry, there have been notable exceptions to this rule as will be described. Furthermore, because the country is a young one and optics is an old science, there is also no tradition of fundamental contributions to classical optics; but, on the other hand, there have been recent important contributions in certain specific fields in optics, notably in spectroscopy, at the universities and in government research laboratories.

The considerable amount of work being performed in the field of optics in Canada is dispersed among a large number of relatively small groups rather than being coordinated into any large body such as an optical institute or a large optical industry. For this reason it is difficult to write a concise general account which would give an accurate impression of activities in optics in Canada. Therefore, instead, what amounts to a descriptive listing of a rather large number of separate groups will be presented, even though the list is by no means complete and is confined to notable examples only.

As one would expect from the small scale of activities in Canada relative to their geographical spread, there is no Canadian optical society, nor would it be practical to have a Canadian "local" section of the Optical Society of America. There is, however, a national committee of the International Commission of Optics and there are active branches of the Canadian Association of Applied Spectroscopists.

This account does not include a description of routine production such as in the spectacle lens industry, operated by subsidiaries of American firms, or in the operations of the Canadian Kodak Company. Neither does it dwell on a description of applications of optical techniques such as are used in research in medicine, aerodynamics, metallurgy, etc., even though there often may be isolated examples of development of techniques. In spectroscopy the distinction between simple application of an optical technique and research in optics is not always straightforward; however, spectrochemical analysis such as used by the metallurgical industry, the mines branch of the government, etc., must generally be considered simply as an application of a known optical technique; where spectroscopy is continually applied to new problems, where new techniques are under development, and where new optical properties are discovered the work will be considered as being included under the heading "optics."

This account is most conveniently presented under three categories: industry, universities, and government laboratories.

Industry

Apart from the spectacle and photographic industry, the first important step in the production of optics in Canada was initiated by the National Research Council in 1939 when it was evident that an optics industry was urgently required. After early consultations with American and British optical firms the government set up a company in July, 1940, for the production of optical glass and instruments as well as radar equipment. The optics section of the National Research Council, then headed by L. E. Howlett, provided the nucleus of the optical division of the new company, Research Enterprises Limited. The optical division of the company, directed by D. C. Jones, was soon capable of producing a large range of optical instruments from raw materials to the finished products. An idea of the size of this company can be gained from the *monthly* production figure attained of optics for 7000 binoculars, 500 short base range finders, 2000 assorted sighting telescopes, panoramic sights, directors, etc., as well as smaller numbers of more intricate optics such as those for long base range finders. In addition to providing the nucleus of the optical division of R.E.L., the optics section of the National Research Council set up a relatively large shop which produced a number of

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complex optical components including, for example, ninety Booth 36 in. (91 cm) $f/6.3$ aerial photographic objectives. In 1945 these relatively large facilities for production were almost completely disbanded, as there did not seem economic grounds for justifying such an optical industry in Canada.

A nucleus of the skills and equipment of R.E.L. was maintained, however, in the Instruments and Electronics Division of Canadian Arsenals, Limited, a government corporation which still operates to undertake development, design, reliability investigations, prototype manufacture, production, and testing related to electronic (such as radar), infrared and other optical devices. In recent years a diversity of instruments has been designed and constructed, from a compound microscope to a 183 cm aerial camera, from spectroscopes to range-finder sights.

The outstanding, and perhaps the only, example of commercial optical production in operation in Canada today is the Leitz plant at Midland, Ontario. This plant was established in 1952 and now comprises more than 3740 square meters of space and a staff of 160 to 170 people including physicists, optical engineers, and designers. The main activity of the company has been the design, development, and manufacture of lenses for the Leica cameras. Examples of lenses wholly designed and developed at this plant are the 125 mm Hektor lens, the 35 mm and the 90 mm $f/2$ Summicron lenses, and the new 65 mm Elmar for the Visoflex 11. The M1, M2, M3, and 111G Leicas are assembled as a secondary operation, and Leicas are serviced for agencies in Central and South America as well as the Far East. In addition to the usual photographic line, the production program has been broadened to include development, design, and manufacture of other kinds of optical equipment such as required for data processing machines, plotting tables, television cameras, alignment devices, and measuring instruments. The photographic line has been extended to include lenses for air reconnaissance cameras, microreproduction cameras, and also military applications (fire control instruments, range-finding sights, mortar and machine gun sights, telescopic sights, binoculars, etc.)

Universities

By far the most important work in optics at Canadian universities has been in the field of spectroscopy. The important work at the University of Toronto which produced early contributions under Professor McLennan (such as the explanation of the auroral green line) was continued by the late Professor Crawford working in atomic spectroscopy and H. L. Welsh in molecular spectroscopy. Professor Welsh and his five colleagues are now engaged in an investigation of the properties of molecules and the nature of molecular forces largely by the use of spectroscopic methods; these include techniques developed in their laboratory, such as the use of multiple Raman reflection tubes with high intensity mercury lamps (now commonly called "Toronto lamps") and pressure-induced infrared spectra of homonuclear diatomic molecules. Studies in the field of optical pumping and masers, with particular emphasis on applications to Raman spectroscopy, are also being undertaken.

At McGill University an important group has been active in spectroscopy since J. S. Foster's well-known work on the Stark effect. Spectroscopy is now less emphasized but some recent work of interest in optics has been done in connection with microwave studies at the Radiation Laboratory.

An active spectroscopy group has been established during the past fourteen years at the University of Western Ontario where R. W. Nicholls and eight colleagues plus graduate students are engaged in research on "laboratory astrophysics" and on photon correlation. The former study aims at providing basic information on processes of excitation of and radiation from atoms and molecules (chiefly diatomic) of importance in astrophysics and aeronomy. Specific attention is directed towards the production of transition probabilities and excitation cross section parameters. Over eighty publications have been produced by this group in the past few years.

At the University of Saskatchewan, D. W. Hunten, A. V. Jones, and others are making spectroscopic studies of the aurora and airglow. This work involves special very large aperture apparatus and photoelectric detection in the infrared and the visible regions of the spectrum. Among the major fields of interest in spectroscopy are the measurement of upper atmospheric temperatures by means of line profiles; studies of excitation mechanisms in auroral spectra; studies of twilight emission; and so on. This research group is located in a favorable auroral zone.

To these examples of university research groups in spectroscopy one could add those at the universities of British Columbia and of Manitoba, McMaster University, the University of Montreal, and so on.

Generally speaking, there are no corresponding university research groups in fields of optics not connected with spectroscopy. However, there are a large number of more or less isolated projects in interferometry, physiological optics, photoelasticity, and so on, which, taken together, amount to a great deal of work which is properly considered "optics." For example, at the University of British Columbia there is no research in optics per se; but in the physics department, in addition to spectroscopic studies in plasma and solid state physics, a large Michelson interferometer is being constructed for use in the 100–200 Å region; Kerr cell shutters and streak photography are

being applied to the study of plasmas; and an optical study of the free surface of rotating liquid helium is in progress. As another example, at McMaster University studies are being made of microwave propagation phenomena with special attention to evanescent waves; and work has recently been initiated for the study of atomic, molecular, and crystal structure by the use of harmonic generation produced by the intense radiation from optical masers.

One important exception to the general lack of university research groups in optics other than spectroscopy is the group under Professor Lansraux and his colleagues at Laval University, Quebec. This group is engaged in research in the formation of images in optical instruments, taking into account diffraction effects. Present projects are the study of hyper-resolution, that is, the possibility of increasing the resolving power well beyond the classical diffraction limit, and the use of amplitude filters for increasing resolving power. Work has also been undertaken on the development of new instruments for astronomy, microscopy, metrology, etc. About fifteen papers on these subjects (mostly in French) have been published.

Government Laboratories

Of the large amount of work on optics and its applications which is carried on in government laboratories, that at the National Research Council provides the example in which the greatest variety is represented. In addition to those of its laboratories directly interested in optics, a number are studying optical techniques for application to other problems. For example, high-speed framing and streak photography have been used in the studies of hydraulics and of heat engines; interferometry is used in the aerodynamics section; studies related to optics are involved in microwave research, etc.

Spectroscopy and the development of spectroscopic techniques are of primary importance to two groups in the Chemistry Division: the molecular spectroscopy section, under H. J. Bernstein, is working on the development of new techniques in connection with its study of bond distances and energies in carbon–carbon bonds in various organic chemicals; in addition to its work on the analysis of specific spectra, the organic spectrochemistry section under R. N. Jones has prepared an atlas of vapor phase infrared spectra, including a study of the effect of instrumental resolution, and is studying the mathematical characterization of infrared band shapes.

The major group in spectroscopy is the well known work associated with G. Herzberg in the Division of Pure Physics. This group normally consists of about twenty scientists and postdoctorate fellows; it publishes about twenty scientific papers annually. Studies are under way at present on electronic spectra of diatomic molecules; microwave spectroscopy; atomic and molecular beam spectroscopy; spectra of simple polyatomic molecules; and the use of the ruby optical maser in Raman spectroscopy. Some work on the theory of molecular energy levels has also been undertaken.

A considerable amount of research in optics other than spectroscopy is being carried out by three sections of the Division of Applied Physics. At present these sections comprise together about fifteen scientists and, in addition to the normal complement of technicians, have available the facilities of an optical shop capable of making and coating optical parts up to one meter in diameter, from diverse materials and to the highest accuracy obtainable.

The instrumental optics section under W. E. K. Middleton and P. D. Carman has carried on the research work in aerial photography, lens film resolving power, and photogrammetric camera calibration initiated by the former optics section under L. E. Howlett. In addition, important work has been done on vision through the atmosphere and on the scattering of light by ground glass and quartz.

In the radiation optics section, G. W. Wyszecki and his colleagues are conducting investigations in the fields of photometry and color vision. In connection with the former, means for the better realization of the primary standard of luminous intensity are being developed and improvements in the techniques of photometry are being worked out; these entail studies of the properties of photoelectric detectors and the possibilities of the use of photon counting in photometry. The work of this section in color vision is widely known among those interested in this field; present projects include improved means of reproduction of the color mixture functions of the standard observer; the characteristics of the newly proposed color mixture functions of a 10° standard observer; and the construction of a seven-field colorimeter to measure the curvature of color space.

The interferometry section, under the direction of the author of this report, is concerned with the production and properties of very monochromatic radiations and their application to measurement. One aspect of this work has resulted in useful contributions to the international program which redefined the International Meter in terms of wavelengths of light and in the development of interference comparators for national length standardization work. Another aspect of the work has involved the study of very small wavelength shifts, the construction of a gaseous atomic beam source and, recently, an investigation of some possible continuous, gaseous optical maser mechanisms. The section also is engaged in research on evaporated thin films.

In addition to the three sections described, the photo-

grammetry section of the Applied Physics Division is primarily concerned with optical and photographic techniques, although research in optics is not a function of the section.

Whereas the National Research Council serves as a notable example of activities in optics in government laboratories, it must not be considered that the proportion of this article devoted to the N.R.C. necessarily represents the amount of work in optics carried out there compared with that at other government laboratories. Special uses of microscopy and spectroscopy are of importance in the Geological and Mines Branches; specialized projection and photographic systems are used in the Surveys and Mapping Branch; the work of the astronomical observatories is practically based on optical techniques, and so on. Studies connected with infrared, high-speed photography, gigacycle modulation of light, solar furnaces, etc., are in progress in the Defence Research Board.

An important example of the work in the latter organization is that carried out at the Canadian Armament Research and Development Establishment, Valcartier, P.Q., by C. Cummings, J. Hampson, and others on interactions of optical radiation in the atmosphere. Particular attention is being given in this work to atmospheric transmission and emission at high altitudes in the spectral region 1 to 8 μ. Measurements of the solar spectrum from 2 to 5 μ with a resolution of 15 cm^{-1} have been made from high altitude aircraft at widely differing latitudes, and higher resolution measurements up to 30 km with a balloon-borne spectrometer are planned for 1962. Measurements of the atmospheric emission spectrum in the region 1 to 8 μ have been made with balloon-borne grating spectrometers. Another technique being exploited is the use of the rocket-borne photometer in order to measure the height of airglow emission by penetration through it. The data being obtained are supplying considerable information about interactions in the upper atmosphere such as, for example, the photochemistry of the ozonosphere.

The foregoing are examples of optics in national government laboratories. Research laboratories are also operated by several of the provincial governments. The following are examples of optics at the British Columbia Research Council: A far infrared (35–70μ) spectrometer using a reflecting zone plate has been constructed to study the absorption spectra of odiferous molecules; color standards have been established for color grading of fruit; optical studies are being made in the course of thin film research; Fizeau fringes are used in the study of the growth habit of metallic whiskers; an optical method is being used to study the interaction between gravity waves and shear flow; interference and phase contrast microscopy is used in biological and forestry research, and so on.

It will have been apparent that it is not possible in an article of the scope of the present one to give anything like a complete description of optics in Canada. One is limited not only by the dispersal of activities into relatively small groups in Canada but by the nature of optics itself, a subject in which most work on fundamental principles has long since been satisfactorily completed but which is continually providing new and powerful techniques in a wide variety of fields.

At the same time it is hoped that a correct general impression of the extent of optical activities in Canada has been given. It has not been possible to quote results of the work described even to an extent which would do justice to the research groups concerned; interested readers must perforce be referred to the laboratories themselves or to the scientific literature. In this connection it is not inappropriate to draw attention to Canadian-written books on optics which have become widely used outside the country, such as Herzberg's books on atomic and molecular spectroscopy, Middleton's book on vision through the atmosphere, and Robertson's introduction to physical optics.

K. J. Bignell *Imperial College*, Barbara Wagner *Vienna*, A. J. Krueger *Inyoken*, and Fuad Saiedy *Damascus*, in Vienna August 1961

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The Optical Society of America was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" The Society invites to membership all who are interested in any branch of optics, either in research, in instruction, in optical or illuminating engineering, in the manufacture and distribution of optical goods of all kinds, or in physiological and medical optics. Further information may be obtained from the Executive Secretary of the Society. **Annual Dues:** Regular members and Fellows, $17.00; Associate members, $13.00; Corporate members, $125.00. These dues include subscription to the Society's official journal, the *Journal of the Optical Society of America*, but not to its other publications.

Photoelectric Analysis of Polarized Light

Wolfgang Budde

The light traverses a rotating polarizer and the relative intensity behind this analyzer is measured photoelectrically as a function of the analyzer azimuth. A Fourier analysis is applied to the values obtained. The Fourier constants are practically equivalent to the Stokes parameters and their relations to other polarization parameters such as the phase difference, the azimuth, and the degree of polarization are given. The method may be applied to light of any wavelength. The theory is demonstrated by some measurements which were made with an especially constructed analyzer drive. For most practical cases a very satisfactory precision in the measurement of the polarization parameters is obtained.

I. Introduction

Polarized light can be specified uniquely by a set of parameters such as the Stokes parameters.[1,2] There are four Stokes parameters to characterize partially polarized light—i.e., a mixture of totally- and unpolarized light—and three independent Stokes parameters to characterize totally polarized light. Other parameters are often used, such as the degree of polarization, the azimuth, and the phase difference, which can be expressed in terms of the Stokes parameters.

The phase difference is usually measured by means of a compensator–analyzer combination,[3–5] but for the measurement of azimuth an analyzer is sufficient. The degree of polarization can be measured either way.[6–8] However, little has been reported on the direct measurement of the Stokes parameters.

The purpose of this paper is to outline a method whereby an analyzer is sufficient to obtain for totally polarized light all three Stokes parameters as well as the phase difference. The method can also be used to determine the azimuth and the degree of polarization for both totally and partially polarized light.

II. Theory

A. Basic Definitions

The basic definition and symbols which will be used throughout the paper are as follows:

A Cartesian coordinate system (x, y, z) is adopted in which the wave normal of monochromatic light is assumed to coincide with the positive z axis. The two components E_x and E_y of the electric vector $\mathbf{E}$, which are located along the x and y axes, respectively, are given by[9]

$$E_x = a_1 \cos(\nu t - \delta_1),$$
$$E_y = a_2 \cos(\nu t - \delta_2), \tag{1}$$

where ν is the frequency, t the time, and a_1, a_2 are the amplitudes along the x and y axes, respectively. The phase constants are indicated by δ_1 and δ_2. The integral $I = (1/T)\int_0^T \mathbf{E}^2\,dt$, with $T = 1/\nu$ being the period, is called the light intensity.

Eliminating νt in Eq. (1) and introducing the phase difference

$$\delta = \delta_1 - \delta_2 \tag{2}$$

one obtains

$$\frac{E_x^2}{a_2^2} + \frac{E_y^2}{a_2^2} - \frac{E_x E_y}{a_1 a_2}\cos\delta = \sin^2\delta, \tag{3}$$

which represents an ellipse as illustrated in Fig. 1.

This ellipse becomes a circle for δ equal to a multiple of $\pi/2$ and $a_1 = a_2$. In this case the light is said to be circularly polarized. Another special case occurs for $\delta = 0$ or multiples of π, when the ellipse degenerates to a (double) straight line and the light is said to be linearly polarized. In the following treatment no distinction is required between the general case of elliptically polarized light and the special cases of circularly and linearly polarized light.

The Stokes parameters for totally polarized light are functions of the amplitudes and the phase difference and are given as follows:

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$$S_0 = a_1^2 + a_2^2,$$
$$S_1 = a_1^2 - a_2^2,$$
$$S_2 = 2a_1a_2 \cos\delta,$$
$$S_3 = 2a_1a_2 \sin\delta. \quad (4)$$

Here S_0 is proportional to the intensity of the light and is related to the other parameters by the expression

$$S_0^2 = S_1^2 + S_2^2 + S_3^2. \quad (5)$$

The Stokes parameters for partially polarized light are somewhat different and the equality (5) does not exist. However, this case will not be treated here.

The analysis of elliptically polarized light will also make use of several other quantities, which are indicated in Fig. 1 and are defined as follows:

φ = azimuth of the ellipse,
$2a$ = length of major axis,
$2b$ = length of minor axis,
$\tan\beta = a_2/a_1$ = ratio of amplitudes,
$\tan\chi = b/a$ = ratio of major and minor axes of ellipse.

The following relations can be found between the given quantities[9]:

$$a^2 + b^2 = a_1^2 + a_2^2$$
$$a^2 - b^2 = (a_1^2 - a_2^2)\cos 2\varphi + 2a_1a_2 \sin 2\varphi \cos\delta$$
$$ab = a_1a_2 \sin\delta. \quad (6)$$

The degree of polarization P is usually defined as

$$P = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \quad (7)$$

where I_{max} and I_{min} are the maximum and minimum intensity, respectively, measured behind a rotating analyzer.

B. Theory of the Method

The relative intensity I of the light passing through the analyzer is measured as a function of the analyzer azimuth α, where α is determined relative to the positive x axis. Assuming that the analyzer is an ideal polarizer one obtains[10]:

$$I = \tfrac{1}{2}(a_1^2 \cos^2\alpha + a_2^2 \sin^2\alpha + a_1a_2 \sin 2\alpha \cos\delta), \quad (8)$$

which can be brought into the form

$$I = C_1 + C_2 \cos 2(\alpha - \varphi), \quad (9)$$

where

$$C_1 = \tfrac{1}{2}(a^2 + b^2) \quad \text{and} \quad C_2 = \tfrac{1}{2}(a^2 - b^2). \quad (10)$$

The parameters C_1, C_2, φ constitute a complete set of parameters characterizing the incident polarized light. They can be determined by measuring the relative intensity at three analyzer azimuths α_i ($i = 1, 2, 3$). In this way three simultaneous nonlinear equations are obtained which can be solved for C_1, C_2, and φ.

However, for practical reasons, which will become evident later on, it is advantageous to measure the relative intensity at a larger number of angles α and determine C_1, C_2, and φ by means of a Fourier analysis, which is equivalent to a least-squares fitting procedure.

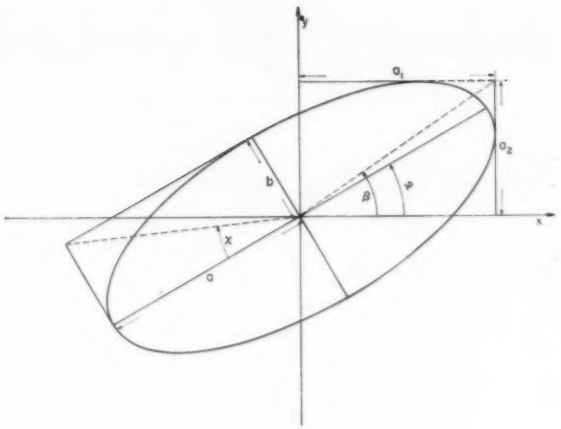

Fig. 1. Parameters of elliptically polarized light. Explanation of the symbols is given in the text.

The Fourier series for Eq. (9) is given by

$$I = k_0 + k_1 \cos 2\alpha + k_2 \sin 2\alpha, \quad (11)$$

where

$$k_0 = C_1,$$
$$k_1 = C_2 \cos 2\varphi,$$
$$k_2 = C_2 \sin 2\varphi, \quad (12)$$

or inversely

$$C_1 = k_0,$$
$$C_2 = (k_1^2 + k_2^2)^{1/2},$$
$$\tan 2\varphi = k_2/k_1. \quad (13)$$

With α_i ($i = 1, 2, \ldots n$) evenly distributed between 0° and 180°, the Fourier constants can be obtained from simple summations:

$$k_0 = \frac{1}{n}\sum_{i=1}^{n} I_i,$$
$$k_1 = \frac{2}{n}\sum_{i=1}^{n} I_i \cos 2\alpha_i,$$
$$k_2 = \frac{2}{n}\sum_{i=1}^{n} I_i \sin 2\alpha_i. \quad (14)$$

Because $\tan 2\varphi = \tan 2(\varphi + \pi/2)$ there are two solutions for φ. The proper one occurs at or near the value of α for which the maximum relative intensity was measured.

The Fourier constants k_0, k_1, k_2, and/or the parameters C_1, C_2, φ can be used to calculate the other polarization parameters mentioned earlier.

1. Stokes Parameters

By means of Eqs. (4), (6), (10), (12), and (13), one obtains

$$S_0 = 2C_1,$$
$$S_1 = 2C_2 \cos 2\varphi,$$
$$S_2 = 2C_2 \sin 2\varphi,$$
$$S_3 = 2(C_1^2 - C_2^2)^{1/2}, \quad (15)$$

and

$$S_0 = 2k_0,$$
$$S_1 = 2k_1,$$
$$S_2 = 2k_2,$$
$$S_3 = 2(k_0^2 - k_1^2 - k_2^2)^{1/2}. \quad (16)$$

It is interesting to note that three of the four Stokes parameters are directly proportional to the Fourier constants.

2. Phase Difference

The phase difference δ can be expressed in terms of the Fourier constants as follows:

$$\cos\delta = \frac{k_2}{\sqrt{k_0^2 - k_1^2}}. \quad (17)$$

For the special cases of linearly polarized light, with $\varphi = 0°$ or $90°$, the expression for $\cos\delta$ becomes indeterminate, since $k_2 = 0$ and $k_0 = k_1$. It is, however, evident that for this case δ must be zero.

3. Degree of Polarization

It can be shown that the minimum and maximum intensities of elliptically polarized light are proportional to b^2 and a^2, respectively. With this and Eq. (10) in mind, the degree of polarization can be expressed as follows:

$$P = \frac{C_2}{C_1} = \frac{\sqrt{k_1^2 + k_2^2}}{k_0}. \quad (18)$$

4. The Parameters tan2χ and tanβ

These are given by the following formulas:

$$\tan 2\chi = \frac{k_2}{\sqrt{k_1^2 + k_2^2}}, \quad (19)$$

and

$$\tan\beta = \sqrt{\frac{k_0 + k_1}{k_0 - k_1}}. \quad (20)$$

It must be emphasized that the above equations refer to totally polarized light. However, some of these equations can also be applied to partially polarized light, which can be considered a mixture of unpolarized and elliptically polarized light. For such a mixture, the relative intensity also fulfills Eq. (9) with the new constant $C_1' = C_1 + 2a_0^2$, where a_0 refers to the unpolarized component. The analysis provides the azimuth φ of the elliptically polarized component as well as the degree of polarization of the mixture. The phase difference δ of the elliptically polarized component and the amount $2a_0^2$ of the unpolarized component cannot be obtained.

C. Precision

In carrying out actual measurements of relative intensities I_i at different azimuths α_i of the analyzer, small errors in I_i will occur. These errors will be propagated through the analysis and consequently will affect the results obtained for the polarization parameters. The application of the theory of error propagation[11] readily shows that, under the assumption that the standard deviations σ_i of I_i are independent of i and are the same for all i, the standard deviations of all polarization parameters are functions of σ_i and I_i and are directly proportional to $(1/n)^{1/2}$, where n is the number of azimuths α_i at which the intensity is measured. With increasing n, the standard deviations of the polarization parameters decrease, which is equivalent to an increase in precision. For most practical purposes $n = 36$ is considered sufficient, i.e., making measurements at intervals of 5° from 0° to 175°. This is a resonable compromise between experimental effort and attainable precision. A further increase of n increases the precision only slowly.

III. Experimental

To demonstrate the theory an analyzer drive has been constructed, the design and application of which is described below.

A. Analyzer Drive

Two short pieces of coaxial brass tubing T_1 and T_2 (see Fig. 2) fitting snugly into each other were mounted at the inner ring of a large precision ball bearing. The inner tube T_1, which carries a sheet polarizer (Polaroid type HN22) can be rotated against the outer tube T_2, to which a protractor is attached by means of a worm gear W_1 to provide precise coincidence between the plane of vibration of the polarizer and the 0° mark of the protractor. Tube T_2 is driven by a synchronous motor linked with T_2 by the gears G_1 and G_2 and the worm gear W_2. At the axis of the worm another gear is mounted, which drives a circular disk D with a small groove. This disk operates a microswitch M; it can be seen in Fig. 3 outside the case. The over-all gear ratio between the protractor and the disk is 1:72 so that at every five degrees of the protractor rotation, the microswitch closes briefly. A protractor rotation of 180° is completed in 4 min. The whole

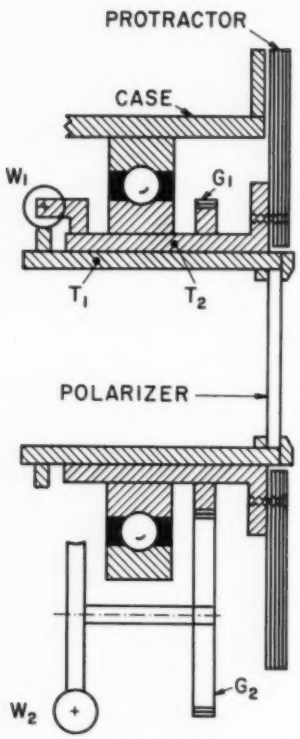

Fig. 2. Schematic diagram of analyzer drive. T_1, T_2—coaxial tubes carrying polarizer and protractor, respectively; W_1—worm for relative adjustment of polarizer and protractor; W_2, G_1, G_2—worm and gears for driving the polarizer–protractor combination by synchronous motor.

mechanism is mounted in a case with a stem and a saddle stand for standard triangular benches. The protractor protrudes at the top of the case where its azimuth α can be read.

An RCA 6217 photomultiplier tube is placed behind the analyzer drive. The photomultiplier output is a measure of the relative intensity of the light transmitted by the analyzer. It is, of course, important that the photomultiplier show no polarization effects; that is, if unpolarized light is analyzed, the photomultiplier output should be constant at all azimuths α_i. Some head-on type multipliers show small polarization effects, but these can be eliminated by, for example, mounting a piece of pot-opal glass in front of the cathode.[12]

The dark current of the photomultiplier is compensated for electrically. It can be shown that the dark current affects k_0 but not k_1 and k_2. Therefore, the dark current has to be compensated for or taken into account by numerical corrections to avoid systematic errors in C_1, P, and δ.

The output of the photomultiplier is fed into a recorder. The contact closures of the microswitch M activate a special marker pen which provides short marks on the graph paper of the recorder at intervals of 5° of protractor rotation.

The analyzer drive is calibrated with respect to its azimuth by analyzing a beam of light for which the azimuth is known. Adjustments are made by means of worm W_1.

B. Examples

An integrating sphere with two lamps inside was used as a source of unpolarized light. A narrow-band interference filter (peak transmittance at $\lambda = 564$ mμ) was mounted at the exit hole of the sphere. The exit hole was imaged through the analyzer onto a pot-opal glass placed in front of the photocathode.

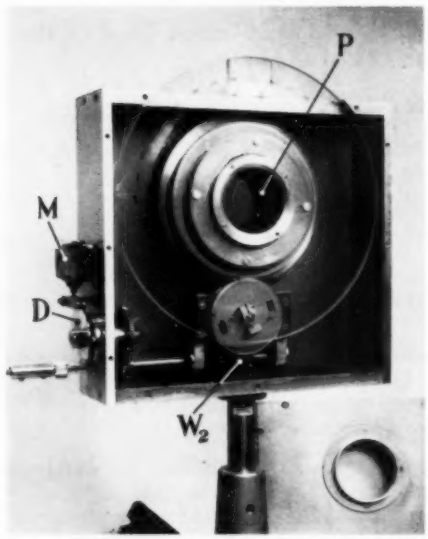

Fig. 3. View of analyzer drive with front plate removed. P—polarizer; M—microswitch; D—disk with groove for contact closure every five degrees of protractor rotation; W_2—worm on motor shaft. (Worm W_1 is mounted behind the ball bearing and cannot be seen.)

The filter for 564 mμ was used because the quarter-wave plate which is used to produce elliptically polarized light [see example (iii)] is made for this wavelength. However, this method of analyzing polarized light is not confined to a specific wavelength since no optical element is used in the analyzing apparatus which is designed for a specific wavelength.

Figure 4 illustrates the multiplier outputs obtained for the following measurements:

(i) *Unpolarized light* coming from the integrating sphere. The output of the photomultiplier as a function of the analyzer azimuth is constant (curve 1). It is obvious that, for this case, $k_1 = k_2 = 0$; thus $C_2 = 0$ and $P = 0$. The azimuth is indeterminate.

(ii) *Linearly polarized light* produced by inserting a linear polarizer between the sphere and the analyzer. The gain of the photomultiplier was increased to provide a maximum multiplier output of approximately 100% (curve 2). By means of Eq. (14) one obtains:

$$k_0 = C_1 = 50.12,$$
$$k_1 = 46.31,$$
$$k_2 = 19.13.$$

From these values and Eqs. (13), (15), (17), (18) it follows that

$$C_2 = 50.11,$$
$$\tan 2\varphi = 0.4130,$$
$$\delta = 0.9980,$$
$$P = 1.000.$$

(iii) *Elliptically polarized light* produced by adding to the previous arrangement a quarter-wave plate positioned between the linear polarizer and the analyzer. The gain of the photomultiplier was again increased to provide a maximum output of approximately 100.

From the analysis one obtains:

$$C_1 = k_0 = 71.97,$$
$$k_1 = -8.56,$$
$$k_2 = 27.09,$$

and

$$C_2 = 28.41,$$
$$\tan 2\varphi = -3.17,$$
$$\cos\delta = 0.3791,$$
$$P = 0.3948.$$

The proper value of the azimuth is given by $\varphi = 53° 45'$.

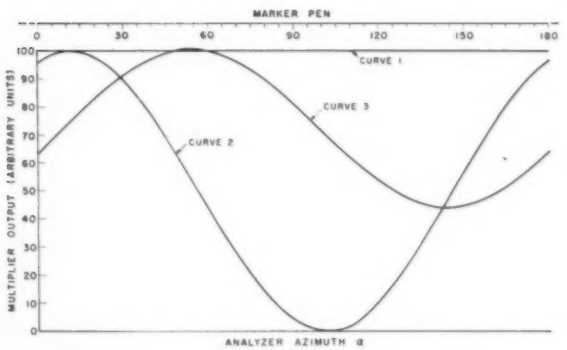

Fig. 4. Photomultiplier output as function of analyzer azimuth α. Curve 1: unpolarized light; curve 2: linearly polarized light; curve 3: elliptically polarized light. The analyzer azimuth is indicated by the marks from the marker pen at the upper edge of the graph.

From repeat measurements it was estimated that the various polarization parameters can be obtained with the following precision:

$$C_0 = k_0 : \pm 0.03$$
$$k_1 : \pm 0.05$$
$$k_2 : \pm 0.05$$
$$C_2 : \pm 0.05$$
$$P : \pm 0.001.$$

The precision of the phase difference δ depends upon the actual value of δ. For small values of δ the errors may be relatively larger but for larger values of δ the errors are relatively small. For example, in case (iii) it was found that $\delta = 67° 42' \pm 2'$. The precision of the azimuth φ depends to a certain extent on the actual value of φ but more strongly on the shape of the ellipse. Obviously the azimuth of linearly polarized light can be determined with higher precision than the azimuth of light which is almost circularly polarized. In examples (ii) and (iii) it was found that $\varphi = 11° 6' \pm 2'$ and $\varphi = 36° 45' \pm 6'$, respectively.

The precision in the values of the polarization parameters can easily be greatly improved by using a more precise photometer, such as that described by Jones and Sanders.[13] With such a photometer, it is estimated that degrees of polarization can be measured with a precision of $\pm 5 \times 10^{-5}$. This precision would correspond to that obtained by Wille[6] and Bauer,[8] who measured small degrees of polarization.

The author is indebted to G. Wyszecki for many helpful discussions. Thanks are also due to R. M. Hamel and L. M. Johnston for the skillful design and construction of the analyzer drive, and to C. Dodd and D. Gignac for their assistance in making and evaluating the measurements.

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From the Editor

Many of us are faced with a problem in keeping up with international optics. The growth of science means that there is so much more to learn. The journals get thicker; the papers harder to understand. We don't get to see foreign journals as often as we would like to, and when we do there is a language barrier. Each new journal (even *Applied Optics*!) just seems to add to our chores. This problem is common to all science. After all, 90 percent of all the scientists who ever existed are alive today. The proliferation of meetings, symposia, and even more papers may delight the publishing and hotel industries, but they are the despair of research people trying to keep abreast of a field. A new body of literature is growing up on the problem of disseminating existing literature. Until some universal computer is developed to solve our problem, I would like to offer several suggestions for those who would understand international optics: (1) use the opportunity to read translations of articles, such as in *Optics and Spectroscopy;* (2) keep in personal touch with scientists and laboratories abroad and with their work through international meetings; and (3) find a survey of this work in condensed and handy form such as we hope we have provided here.

Optics is a relatively old science, and one rich with contributions from scientists all over the world. There are great differences, however, in the traditions and patterns of research in different countries. Certain countries have a history of outstanding contributions to optics. In others, optics research tends to be isolated and relatively meager, for their physics has flowered in other fields. There are reasons for these differences. In some countries every budding physicist must spend a lot of time—up to 2 years—understanding optics. Others—such as the United States—require only a short course. Sometimes a national pattern of research in optics has been set by a few brilliant and dynamic people at a single institute or university. The presence of an optical industry will dramatically affect the pattern of physics research, not only through the basic research that it supports, but through attracting students into the field and encouraging the training of technicians and scientists in applied optics.

Whatever the type of research being carried out, it is always rewarding to visit a foreign scientist and laboratory. Not only will you improve your knowledge of the field, but you will get a glimpse of the country which is more interesting and penetrating than that afforded by the standard rubberneck tour. The opportunity to go to international meetings (such as the ICO meeting in Munich this August) should be grasped by anyone who can afford the time and trip. Here you can meet and talk with many of the people mentioned and writing herein—the leaders of international optics.

D. Z. Robinson

We have already spoken in this column of the unsung heroes who, by reporting, reviewing, and refereeing, are indispensable to the successful operation of the journal. Perhaps the most heroic of all are the Feature Editors—those responsible for the featured topic of each issue—for on them falls the primary burden of luring to our journal the topical material that is ripe for publication. The Editor was advised early in the game not to utilize this space to praise the Feature Editors: if you do it for one you will have to do it for them all. But the best advice is that which is ignored, so here goes. It seems to us that we owe a particular debt of gratitude to the first three Feature Editors, more than to all the others that come later, because these three were working in the dark. They wrote to colleagues and co-workers describing a journal that did not yet exist, which no one had seen, but in which they should nevertheless publish. Furthermore, it was essential that the journal get off to a good start, for the entire tone of the journal can be set by the enthusiasm and momentum of the first few issues. The Feature Editors yet to perform will still have to labor to maintain this momentum, but they should no longer have to persuade reluctant authors that this is indeed an honest, upright, and respectable journal.

Bruce Billings, our Pumping Editor, had the most difficult job, being the earliest in time. Furthermore, the sudden and explosive development of this field of masers, irasers, lasers, and quasers, although concerning optical radiation, was initially dominated by the solid-state physicists and electronic engineers, most of whom felt no kinship with optics or the Optical Society. Look at the articles of the first issue; how few of their references are to optical journals. Our issue on this feature was most timely: we now have many more papers on optical pumping waiting to be published. Perhaps we can yet become the focal point, the publishing home for this subject.

Lloyd Mundie, our Space Optics Editor, drew on his broad knowledge of the present status of space research to assemble a splendid issue on Space. These papers run the gamut from the vacuum ultraviolet to the infrared and from ground-based to airborne, balloon-borne, and even satellite-borne optical studies. Shortly after the first Sputnik your Editor was on a program committee for a meeting reporting on infrared studies. We enthusiastically chose as our theme "Infrared in the Space Age," and then at the meeting found to our disappointment that many of the papers were little more than proposals: we simply were not in the Space Age. But now space studies are a reality, and bigger and better and more exciting optical studies of space and from space platforms should help fill many future issues of *Applied Optics*.

David Robinson, our International Optics Editor, performed the third miracle in a row. He was not appealing to workers to return to optics from journals of other disciplines, but rather bridging the national and language boundaries that separate and divide us. Many foreign workers are encouraged to publish in their own national journals, and are reluctant to publish in the standard journal of another national society. Simply having the word American in the title seems to be a deterrent. Many foreign workers who read and speak English fluently become suddenly shy about trying to write it. We are indeed sponsored and published by a national society, but we are not its official organ, and our multilingual nature should encourage foreign participation. Certainly this issue should demonstrate that optics people the world over can be persuaded to contribute to a common journal.

We owe much to these first three Feature Editors, whose efforts really launched the journal so successfully.

The featured topics for the first three issues: Optical Pumping, Space Optics, and International Optics have pretty much dominated the entire issue. The Editor looks forward to the day when these features can be held to a smaller proportion of the journal, so that there is more room for the contributed papers on other topics. We welcome your suggestions of topics to highlight in future issues. When we become a monthly next year we have immediate openings for six new topics. We need topics that are interesting and timely, and so interesting and so timely that the Editor is buried under the avalanche of papers!

J. N. Howard

A Photocell Linearity Tester

C. L. Sanders

Illumination provided by an apparatus with nine pairs of apertures may be used conveniently to test the linearity of photometers. The apertures increase in area from one pair to the next by a factor of two. Thus the range covered is 512 to 1. The apertures are selected individually or in pairs by holes in a rotatable disk. The photometer reading on each illumination level in a pair is determined, and the numerical sum of these is compared with the reading on the two together. The ratio can be used to correct the photometric scale of the receiver. The advantage of this apparatus is the straightforward method of selecting illumination levels, the wide range of illumination, and the easily arranged equipment.

Introduction

The linearity tester described below falls into the class of step sources. The step source system is based on the fact that a linear photometric device which gives a reading of A for an illuminance of A' and a reading of B for an illuminance of B' will give a reading of $A + B$ when illuminance B' is added to illuminance A'. If the reading of C on the composite light is not equal to $A + B$, the device is nonlinear and a correction factor must be applied. The correction factor for C is $(A + B)/C$. The usual arrangement with the step source technique of a calibrating photometer is to have several (up to 10) sources of approximately equal intensity and to measure each of these in turn and then to measure combinations of these. This procedure provides a calibration over a range of 10:1 in illuminance. The experimenter must keep an accurate record of his selection and ensure that each shutter is properly opened or closed. The experiment is therefore rather tedious and susceptible to human error. In our laboratory a box with eight separate lamps was available. Each lamp was in a separate compartment covered by a sliding shutter. The apparatus was inconvenient to use, with the result that the linearity of our photoelectric devices was rarely checked. The device to be described simplifies the procedure by providing a means of readily opening and closing selected apertures.

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This paper was presented at the OSA Meeting in October 1960 at Boston, Mass.

Description of the Apparatus

The apparatus shown in Fig. 1 contains a 6-volt, 18-amp, strip-filament projection lamp with a T10 bulb and an SR8 filament. In order to reduce stray light, all the metal parts are chemically blackened and the lens has an antireflection coating. An image of the filament is formed at a variable distance from the achromatic lens, and the photocell to be tested is placed at this image of the filament. The maximum illuminance of the photocell may be adjusted by varying the lamp voltage or by placing a neutral filter in the beam.

The luminance of the strip filament is nearly constant over its area; therefore the receiver is uniformly illuminated when the image of the strip is larger than the limiting aperture of the receiver. During the linearity test only the aperture of the lens is varied and consequently the image of the filament remains fixed in size and position, when the lens is corrected for spherical aberration.

All the apertures which may be selected to pass light to the photocell are drilled in a master plate. The illuminance on the photocell is proportional to the area of aperture which is selected. These apertures are divided into 9 pairs. The area of each pair is twice that of the preceding pair and therefore the illuminance on the photocell is approximately doubled each time a larger aperture is selected. The diameter of the smallest aperture is 0.81 mm and of the largest is 12.7 mm. The apertures are selected by holes drilled in a disk which may be rotated about its axis. The aperture is positioned by first releasing the ball from the dimple by means of the conveniently located release lever and then rotating the selector disk until the letter,

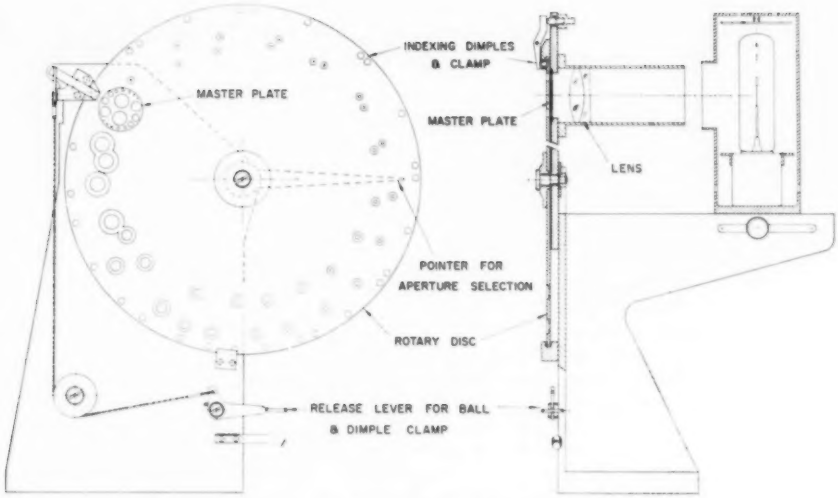

Fig. 1. Photocell linearity tester.

indicating the desired aperture or pair of apertures, is opposite the pointer. The lever is then released and the ball is pressed into the corresponding dimple to locate the disk accurately. The holes in the selector disk are 0.8 mm larger in diameter than the holes in the master plate which provide the limiting apertures. The smallest holes are selected at A and a, respectively, and if the pair is to be selected the pointer is set at A, a. The other apertures are marked correspondingly as B, b, C, c, and so on. Since there are 9 pairs of apertures each with twice the area of the preceding pair, the complete illuminance range is 2^9 (or 512) to 1.

The maximum illuminance available depends on the operating color temperature of the strip filament which is used and on the distance from the apertures to the receiver. The image size depends on the distance from the filament to the lens. The image widths corresponding to a strip filament 2 mm × 18 mm are given in Table I for a number of image distances. The maximum illuminance at each image position is given for strip-filament color temperatures of 2042°K and 2854°K. It should be noted that the maximum illuminance for an image 50 mm wide is only 100 lu/meter² which is much lower than the illuminance required to calibrate certain illumination meters which may operate up to 100,000 lu/meter² or approximately 10,000 ft-c. Nevertheless most photometric instruments can be calibrated since they either operate to a lower maximum illuminance or have a smaller receiver area.

Table I. Maximum Illuminance at Image under Various Conditions

Image width (mm)	Distance from image to apertures (cm)	Maximum illuminance at 2042°K (lu/meter²)	Maximum illuminance at 2854°K (lu/meter²)
2	20	1300	21000
5	37	370	6100
10	66	120	1900
50	290	6.0	100

The procedure for calibrating a photocell is to measure the 27 illuminances provided by the individual and paired apertures and analyze them as indicated in Table II. The letters now indicate the reading on the photometer. The sum of each pair of individual readings is calculated and recorded in column 2. The ratio between the reading on the pair measured together and the corresponding calculated sum is given in column 3. Only relative correction factors can be determined. Therefore the correction factor for any one net reading may be chosen equal to unity. If the largest reading (Ii) is chosen, the factors for the other readings are found as given in the fourth column of Table II. The last column contains the reading to which the correction factor is applicable. Alternate correction factors may be determined by dividing each factor in Table II by a constant factor as is illustrated in Table III, where it is assumed that no correction is required to the reading $(E + e)/2$. Thus the correction factors in Table III are determined by dividing each correction factor in Table II by

$$\frac{Ee}{E+e} \cdot \frac{Ef}{F+f} \cdot \frac{Gg}{G+g} \cdot \frac{Hh}{H+h} \cdot \frac{Ii}{I+i}.$$

Table II. Determination of Factors to Correct Readings to a Linear Scale

Net reading	Sum	Ratio	Correction factor[a]	Correction applies to reading
A			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}\cdot\frac{Ee}{E+e}\cdot\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}\cdot\frac{Bb}{B+b}\cdot\frac{Aa}{A+a}$	$\frac{A+a}{2}$
Aa	$A+a$	$\frac{Aa}{A+a}$		
a				
B			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}\cdot\frac{Ee}{E+e}\cdot\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}\cdot\frac{Bb}{B+b}$	$\frac{B+b}{2}$
Bb	$B+b$	$\frac{Bb}{B+b}$		
b				
C			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}\cdot\frac{Ee}{E+e}\cdot\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}$	$\frac{C+c}{2}$
Cc	$C+c$	$\frac{Cc}{C+c}$		
c				
D			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}\cdot\frac{Ee}{E+e}\cdot\frac{Dd}{D+d}$	$\frac{D+d}{2}$
Dd	$D+d$	$\frac{Dd}{D+d}$		
d				
E			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}\cdot\frac{Ee}{E+e}$	$\frac{E+e}{2}$
Ee	$E+e$	$\frac{Ee}{E+e}$		
e				
F			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}\cdot\frac{Ff}{F+f}$	$\frac{F+f}{2}$
Ff	$F+f$	$\frac{Ff}{F+f}$		
f				
G			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}\cdot\frac{Gg}{G+g}$	$\frac{G+g}{2}$
Gg	$G+g$	$\frac{Gg}{G+g}$		
g				
H			$\frac{Ii}{I+i}\cdot\frac{Hh}{H+h}$	$\frac{H+h}{2}$
Hh	$H+h$	$\frac{Hh}{H+h}$		
h				
I			$\frac{Ii}{I+i}$	$\frac{I+i}{2}$
Ii	$I+i$	$\frac{Ii}{I+i}$	1.000	Ii
i				

[a] Assuming no correction to reading of Ii.

Table III. Factors to Correct Readings to a Linear Scale

Average net reading	Correction factor[a] for average net reading
$(A+a)/2$	$\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}\cdot\frac{Bb}{B+b}\cdot\frac{Aa}{A+a}$
$(B+b)/2$	$\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}\cdot\frac{Bb}{B+b}$
$(C+c)/2$	$\frac{Dd}{D+d}\cdot\frac{Cc}{C+c}$
$(D+d)/2$	$\frac{Dd}{D+d}$
$(E+e)/2$	1.000
$(F+f)/2$	$\frac{E+e}{Ee}$
$(G+g)/2$	$\frac{E+e}{Ee}\cdot\frac{F+f}{Ff}$
$(H+h)/2$	$\frac{E+e}{Ee}\cdot\frac{F+f}{Ff}\cdot\frac{G+g}{Gg}$
$(I+i)/2$	$\frac{E+e}{Ee}\cdot\frac{F+f}{Ff}\cdot\frac{G+g}{Gg}\cdot\frac{H+h}{Hh}$
Ii	$\frac{E+e}{Ee}\cdot\frac{F+f}{Ff}\cdot\frac{G+g}{Gg}\cdot\frac{H+h}{Hh}\cdot\frac{I+i}{Ii}$

[a] Assuming no correction to reading of $(E+e)/2$.

Table IV. Linearity Check of Selenium Photocell

Reading name	Net reading	Sum	Ratio $Nn/(N+n)$	Correction factor	Reading at which factor applies $(N+n)/2$
A	0.14		1.07	1.13	0.14
Aa	0.30	0.28			
a	0.14				
B	0.31		1.03	1.06	0.31
Bb	0.64	0.62			
b	0.31				
C	0.64		1.02	1.03	0.62
Cc	1.27	1.25			
c	0.61				
D	1.32		1.004	1.011	1.28
Dd	2.58	2.57			
d	1.25				
E	2.68		1.008	1.007	2.61
Ee	5.26	5.22			
e	2.54				
F	5.30		1.006	0.999	5.22
Ff	10.49	10.43			
f	5.13				
G	10.92		1.000	0.993	10.7
Gg	21.44	21.43			
g	10.51				
H	21.12		0.997	0.993	21.4
Hh	42.67	42.79			
h	21.67				
I	42.90		0.996	0.996	42.6
Ii	84.95	85.31			
i	42.41		1.000	1.000	85.0

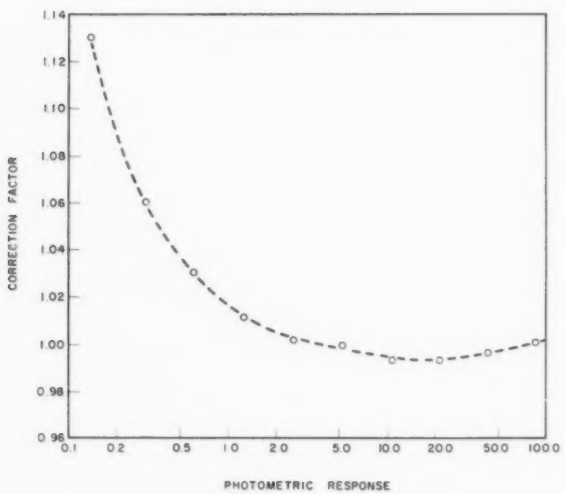

Fig. 2. Graph showing the correction factors for a photometer using a selenium photovoltaic cell.

Once the correction factors have been found, a graph must be prepared before the corrections can be applied to the readings of a practical photometric test. The correction factor $Ii/(I+i)$, for the net reading I, is plotted against I if the readings I and i are identical. In general the readings I and i are different and therefore the correction factor is applied to the average of the two, that is $(I+i)/2$. The other points are plotted similarly and a curve is drawn. Then the correction factor for any photometric reading, obtained with the same photometric circuit, may be easily read from the graph. Since both the photocell and the associated apparatus are being tested, any nonlinearity which is found cannot be connected for certain with the nonlinearity of the photocell unless the associated apparatus has been separately calibrated.

The measurements and calculations required to find the correction factors for a selenium photovoltaic cell photometer are shown in Table IV. The graph for determining the correction factor at any photometric response is shown in Fig. 2. This photometer is far from linear at responses less than 2.0 with a correction of 13% at the reading of 0.14. The results for a photometer using a Gillod-Boutry type photocell[1] are given

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in Table V and the correction graph in Fig. 3 shows that both the photocell and the associated circuit are very nearly linear. The photometer reads high by 0.3% at a reading of 175 when the correction factor is normalized at a reading of 90,500. This represents a range of over 500 to 1.

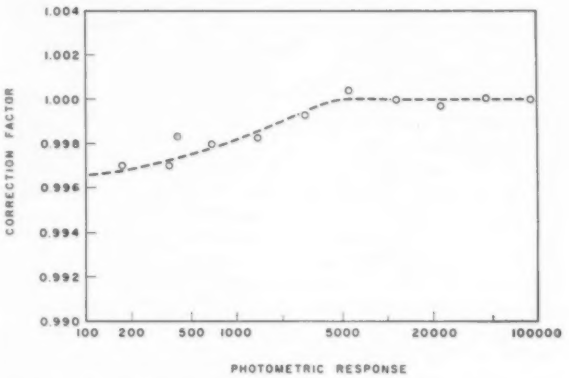

Fig. 3. Graph showing the correction factors for a photometer using a Gillod–Boutry type vacuum photocell.

Reference

1. O. C. Jones and C. L. Sanders, J. Opt. Soc. Am. **51**, 105 (1961).

Table V. Linearity Check of Photometer Using Gillod–Boutry Photocell

Reading name	Net reading	Sum	Ratio $Nn/(N+n)$	Correction factor	Reading at which factor applies $(N+n)/2$
A	173		1.000	0.997	175
Aa	350	350			
a	177				
B	352		0.999	0.997	355
Bb	709	710			
b	358				
C	676		1.000	0.998	681
Cc	1363	1363			
c	687				
D	1412		0.999	0.9983	1398
Dd	2792	2795			
d	1383				
E	2856		0.9989	0.9993	2816
Ee	5627	5633			
e	2777				
F	5615		1.0004	1.0004	5569
Ff	11142	11138			
f	5523				
G	11485		1.0003	1.0000	11340
Gg	22690	22684			
g	11199				
H	22375		0.9996	0.9997	22570
Hh	45120	45140			
h	22775				
I	45341		1.0001	1.0001	45240
Ii	90486	90479			
i	45138		1.000	1.0000	90500

continued from page 212

in spectroscopy by G. R. Harrison, R. C. Lord, and others. But any survey of optical activities in the U.S.A. will show Greater Boston as one of the areas of major importance, and this fact was not overlooked in picking the site for this successful meeting, whose theme was "Frontiers in Physical Optics." At the accompanying business meeting the writer was elected president of the ICO for a three-year period.

A colloquium on "Optics in Metrology" was arranged for Brussels in 1958, held appropriately enough in May, during the early days of the Brussels World Fair. The next ICO congress met in Stockholm, Sweden, in late August 1959 and was very well attended, especially by Americans. This was the first ICO meeting at which much attention was given to electronic methods, information handling techniques, and some of the other more modern aspects of our broad field. Erik Ingelstam was elected president of the ICO for the period 1959–62—he is Director of the Institute of Optical Research of the Royal Institute of Technology in Stockholm and is responsible for a goodly portion of Swedish activity in optics, although again there is work underway at the astronomical observatories and the other Swedish universities. Two specialized colloquia were held under ICO sponsorship in the summer of 1961, as is described briefly in the January 1962 issue of *Applied Optics* (Vol. 1, pp. 80–81). Optical materials, films, filters, and polarizers were discussed in Paris on July 5–8, and optical instruments, techniques, and systems in London the following week.

The sixth congress of the ICO will be held on August 20–25, 1962, in Munich, Germany, with arrangements being made by a committee headed by Prof. Dr. Dr. H. Schober of the Institute for Medical Optics of the University of Munich. You will be reading more about this meeting in the pages of *Applied Optics* and elsewhere, and some of you will join us in the group flight to Europe on July 30.

Those of us who have been fortunate enough to participate in the activities of the International Commission of Optics for the past fifteen years agree that this has been a most happy experience in the free exchange of scientific ideas in a fashion that has completely transcended national boundaries. I believe that optics has been a leader in such open-armed international cooperation, and I hope that many more American scientists will be able to participate in similar worthwhile endeavors in the years to come.

Applied Optics

Optical Activities in the Universities

reported by STANLEY S. BALLARD, Department of Physics, University of Florida, Gainesville, Florida. Professor Ballard hopes to receive news and comments for this column, which should be sent to him at the above address

In assessing the status of academic optics in the U.S.A. it is only natural to look for comparisons between our situation and that existing in the various countries of Europe. In general, the conclusion drawn from such comparisons is that optics is treated as a more important field of physics in Europe than in America. Many of the foreign universities have professors of optics or professors of physics whose acknowledged specialty is optics. Several countries have national institutes of optics, as described in other pages of this issue, and in still other countries there are departments of optics in the important technological institutes. It surprises an American physics professor to find that optics receives so much more consideration in the educational systems of such countries as France, England, Italy, Spain, Netherlands, Sweden, and of course Germany, and he naturally wonders about the source of this difference in comparative treatment. One consequence of the international contrast in the importance of optics has been mentioned before, namely, that the U.S.A. has found it necessary to import its leaders in theoretical optics largely from abroad—this certainly indicates that we are not training sufficient numbers of such people here in our own country. Some gestures of a compensatory nature have been made for this raiding activity via the support given to optical research abroad by our governmental agencies, especially the U.S. Air Force. However, it seems that we should surely be able to train our own optical specialists in America, and this was the general theme of my March column which described a National Institute of Modern Optics that has been proposed by a group of scientists from the Boston area.

The present issue of *Applied Optics* features optical activities in countries other than the U.S.A. I would like to offer some supplementary comments based on my experience in the International Commission of Optics, which is the organization that has done so much to unify points of view on optical research among the nations since the end of World War II. It was then realized by many people that there had been a hiatus of several years during which the interchange of scientific information in optics (and in other sciences) had been severely interrupted. Optics is from its very nature an international discipline, being second perhaps only to astronomy in this respect. Therefore, and at the initiative of Professor P. Fleury of France, a conference called the "Réunions d'Opticiens" was held at the Institut d'Optique in Paris, in October 1946. (One of those attending was Dr. Mary E. Warga, now OSA Executive Secretary.) Representatives from sixteen countries decided that an International Commission of Optics should be organized, under the aegis of the existing International Union of Pure and Applied Physics. A preparatory meeting for this purpose was held in Prague, Czechoslovakia, in June 1947, with representatives of eight countries attending. The objectives and organization of the new Commission were defined and provisional statutes for its government were drawn up. The first regular meeting was scheduled for Delft, Holland, in July 1948. Eleven countries were represented at the Delft meeting, and these became the first member countries of the ICO. Thomas Smith, British scientist so well known for his lens design techniques, was elected the first president of the Commission; P. Fleury of France became the first secretary. The Delft meeting gave the delegates a chance to see in action some of the optical activity in the small but scientifically vigorous Netherlands. The meeting was held in the Technical University (the M.I.T. of the Netherlands), and the arrangements were made by A. C. S. van Heel, who is professor of technical optics in that institution.

The second regular meeting of the Commission was held in London in July 1950, at the Imperial College of Science and Technology. Our hosts were such optical figures as T. Smith, E. W. Taylor, L. C. Martin, well known for his books on technical optics, and W. D. Wright of color vision fame. The London meeting was accompanied by the London Conference on Optical Instruments, the proceedings of which have appeared in book form. Professor van Heel was elected president of the ICO, succeeding T. Smith. It was decided in London that full meetings of the ICO should be held with a three-year frequency, but that smaller colloquia on specialized subjects could be held between the main congresses. Thus a colloquium on phase contrast techniques was held in Paris in the summer of 1951 and one on optics and microwaves in Milan in 1952.

The third congress of the ICO, held in Madrid in 1953 and attended by delegates from twelve countries, provided an opportunity to see the work going on at the Instituto de Optica, which is one of the major research institutes of Spain. Interestingly enough, optics is a most important research science in Spain, second perhaps only to nuclear physics—doubtless because Professor J. M. Otero, one of the most vigorous scientific-political figures of Spain, is an optics man. At this meeting the earlier plans to found a new European journal of optics were brought to successful completion with the establishment of *Optica Acta*, which commenced publication the following year. The scientific sessions accompanying the Madrid meeting bore the title "Optical Problems of Vision."

A small conference on infrared physics was held in Parma, Italy, in September 1954 under ICO sponsorship. Also held that month, in Florence, Italy, was a colloquium "Problems in Contemporary Optics," sponsored by the National Institute of Optics of Italy. This occasion provided several of us from the U.S.A. with a welcome opportunity to visit this famous research institute, where so much fine work has been done by its director, V. Ronchi, and his two daughters, by G. Toraldo di Francia, Miss A. Fiorentini, and others—again in Italy we find emphasis on optical research as an accepted facet of the scientific scene.

The fourth congress of the Commission was held in the U.S.A. in March 1956, at the Massachusetts Institute of Technology. This location was appropriate in view of the extensive work done in photometry and colorimetry by Arthur H. Hardy and

continued on previous page

Population Inversion in a Discharge in a Mixture of Two Gases

N. G. Basov and O. N. Krokhin

Conditions are considered for the formation of a population inversion in a gas discharge in a two-gas mixture, the atoms of which have equal energy levels.

Methods for obtaining population inversion in a gas discharge were discussed by Sanders[1] and Javan.[2] A theoretical study of the conditions for the formation of a population inversion in a gas discharge, including the case of a two-component gas mixture, was conducted by Javan.[2] Population inversions were experimentally realized in refs. 3 and 4, and, apparently, also in refs. 5 and 6.

We have considered the kinetics of a gas discharge in a gas mixture, the atoms of which have identical energy levels.[7] It has been shown that the interaction between atoms of different gases, consisting of a resonant transfer of the excitation energy during collisions (inelastic collisions between atoms), causes the relative density of excited atoms of both gases to approach the same limit. This means that the transfer of energy proceeds in such a way that the ratio N^*/N for gases of both kinds tends to become equal, where N and N^* are the numbers of atoms of a given kind in the ground and in the excited states, respectively.

In other words, if the degree of excitation is described by an effective temperature T (for a given energy level) according to the equation $N^*/N = \exp(-E/kT)$, where E is the excitation energy and k is the Boltzmann constant, then the process under consideration leads to an equalization of the effective temperatures of both gases. In this case, if one of the gases is excited at a higher temperature, the resonant transfer of excitation causes the relative density of excited atoms of the second gas to increase, and this may produce population inversions in the latter gas with respect to lower excited energy levels.

We shall consider the kinetics of this process in more detail and more rigorously than was done by us previ-

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This paper has been translated in view of the small number of our readers who are familiar with the Russian language.

Метод получения состояний с отрицательной температурой в газовом разряде рассматривался в работах Sanders'a[1] и Javan'a.[2] Теоретическое исследование условий возникновения отрицательной температуры в газовом разряде в том числе и в двухкомпонентной смеси газов было проведено Javan'ом.[2] Экспериментально состояние с отрицательной температурой было осуществлено в работах 3 и 4, и повидимому, 5 и 6.

Нами была рассмотрена кинетика газового разряда в смеси газов, атомы которых имеют совпадающие уровни энергии.[7] При этом было показано, что взаимодействие атомов различных газов, связанное с резонансной передачей при соударении энергии возбуждения (неупругие удары между атомами) приводит к тому, что относительная плотность возбужденных атомов для газов различного сорта стремится к одному и тому же пределу. Это означает, что процесс передачи энергии идет в таком направлении чтобы отношение N^*/N для газов обоих сортов стремилось к равенству. Здесь N и N^* плотности числа атомов, находящихся соответственно в основном и возбужденном состоянии для газа определенного сорта.

Другими словами, если степень возбуждения описывать эффективной температурой T (для данного уровня энергии) согласно формуле $N^*/N = \exp(-E/kT)$ (E—энергия возбуждения, k—постоянная Больчмана), то рассмотренный выше процесс приводит к выравниванию эффективных температур обоих газов. Если один из газов возбужден с большей температурой, то процесс резонансной передачи возбуждения приводит к тому, что плотность возбужденных атомов другого газа увеличивается, что может быть причиной возникновения состояний с отрицательной температурой в этом газе по отношению к вышележащим возбужденным уровня энергии.

Отрицательная Температруа в Газовом Раэряде в Смеси Двух Газов.—Н. Г. Басов, О. Н. Крохин, Физический Институт им. П. Н. Лебедева АН СССР, Москва.

ously,[7] and shall consider the case of only two gases. The atoms of the "working" gas "a" shall have three energy levels: $E_1 = 0$ (the ground level), E_2, and E_3. The atoms of the auxiliary gas "b" have two levels, $E_1 = 0$ and E_3.

The rate of change of the number of atoms of gas "a" that are on the level E_3 is

$$\frac{dN_3^a}{dt} = N_1^a\left(\frac{1}{\theta_{13}} + \frac{1}{t_{ba}}\right) - N_3^a\left(\frac{1}{\theta_3} + \frac{1}{t_{ab}} + \frac{1}{\tau_3}\right), \tag{1}$$

where N_3^a and N_1^a are the numbers of atoms of the gas "a" that are on levels E_3 and E_1, respectively; $1/\theta_{13} = n.\overline{\sigma_{13}v}$ is the rate of excitation per atom from level E_1 to level E_3 by electron collisions of the first kind; $1/t_{ba} = N_3^b\overline{\sigma_{ba}v}$ is the rate per ground state atom of gas "a" of resonant transfer of energy from an excited atom of gas "b" to level E_3 of gas "a"; and $1/t_{ab} = N_1^b\overline{\sigma_{ab}v}$ is the rate per excited atom of gas "a" for the inverse process. n, N_3^b, and N_1^b are the numbers of electrons, or excited atoms, and of atoms in the ground state in the gas "b," respectively. σ is the cross section of the process under consideration, v is the relative velocity of colliding particles, and $\overline{\sigma v}$ is the average kinetic energy of the particles. $1/\theta_3$ is the total transition rate per atom from level E_3 (including transitions to levels E_1 and E_2) resulting from collisions of the second kind with the electrons; $1/\tau_3$ is the total transition rate from level E_3 (including that to the level E_2) arising from the remaining relaxation processes (τ_3 is essentially the radiative lifetime). In Eq. (1) a term is not considered which corresponds to the excitation from level E_2 to level E_3; this appears to be justified, since the term is proportional to N_2^a, and since $N_2^a \ll N_1^a$ always holds, the main process of excitation is described sufficiently well by the term N_1^a/θ_{13}.

The rate of change of the number of atoms N_2^a on level E_2 is given by

Мы рассмотрим более детально и строго, чем это сделано нами в работе,[7] кинетику процесса, ограничиваясь случаем двух газов. Атомы "рабочего" газа "a" имеют три уровня энергии $E_1 = 0$ (основной), E_2 и E_3. Атомы вспомогательного газа "b" имеют два уровня $E_1 = 0$ и E_3.

Скорость изменения числа газа "a," находящихся на уровне E_3 равна:

где N_3^a и N_1^a число атомов газа "a," находящихся соответственно на уровнях E_3 и E_1, $1/\theta_{13} = n.\overline{\sigma_{13}v}$—вероят ность возбуждения атома с уровня E_1 на уровень E_3 при соударении первого рода с электронами, $1/t_{ba} = N_3^b\overline{\sigma_{ba}v}$—вероятность резонансной передачи энергии с возбужденного атома газа "b" атомам газа "a," $1/t_{ab} = N_1^b\overline{\sigma_{ab}v}$—вероятность обратного процесса. n, N_3^b, N_1^b—соответственно плотность электронов, возбужденных атомов и атомов в основном состоянии в газе "b." σ—сечение рассматриваемого процесса, v—относительная скорость сталкивающихся частиц, выражение $\overline{\sigma v}$ усреднено по кинетической энергии частиц. $1/\theta_3$—полная вероятность перохода атома с уровян E_3 (включающая переход на уровни E_1 и E_2) в результате соударений второго рода с электронами, $1/\tau_3$—полная вероятность перехода с уровня E_3 (в том числе и на уровень E_2), включающая все остальные процессы релаксации (в основном τ_3—радиационное время жизни). В формуле (1) не учтен член, соответствующий возбуждению атома с уровня E_2 на уровень E_3, что повидимому справедливо, так как он пропорционален N_2^a, в то время как всегда имеет место $N_2^a \ll N_1^a$ и потому основной процесо возбуждения описывается достаточно точно членом N_1^a/θ_{13}.

Для скорости изменения числа атомов N_2^a, находящихся на уровне E_2 имеет место равенство:

$$\frac{dN_2^a}{dt} = \frac{N_1^a}{\theta_{12}} + N_3^a\left(\frac{1}{\tau_{32}} + \frac{1}{\theta_{32}}\right) - N_2^a\left(\frac{1}{\theta_{21}} + \frac{1}{\tau_{21}}\right), \tag{2}$$

where $1/\theta_{12}$ is the rate of excitation by electrons; $1/\theta_{21}$ is the rate for the inverse process; $1/\theta_{32}$ is the transition rate from level E_3 to level E_2 arising from electron collisions; $1/\tau_{32}$ is the rate for the same transition produced by all other processes; and $1/\tau_{21}$ is the transition rate from level E_2 obtained in the absence of electron collisions. In the stationary case $dN/dt = 0$, and the condition for the existence of a population inversion between the E_3 and E_2 levels in the gas "a" is given by the inequality

где $1/\theta_{12}$—вероятность возбуждения электронами, $1/\theta_{21}$—вероятность обратного процесса, $1/\theta_{32}$—вероятность перехода с уровня E_3 на уровень E_2 вследствии соударения с электронами, $1/\tau_{32}$—то же в результате всех остальных процессов, $1/\tau_{21}$—вероятность перехода с уровня E_2 без учета соударений с электронами. В стационарном случае $dN/dt = 0$ и требование наличия отрицательной температуры между уровнями E_3 и E_2 в газе "a" приводит к неравенству:

$$N_3/N_2 > 1. \tag{3}$$

From inequality (3) the required condition can be obtained for the absolute density of excited atoms in the "b" gas, considering the ratio N_1^b/N_3^b as an external parameter, i.e., the effective excitation temperature for atoms of the gas "b" shall be considered as given. For the sake of simplicity, we shall assume a Maxwellian energy distribution for the electrons, with temperature T; since the average electron energy is comparable with the excitation energy of the atoms, the deviation of the actual distribution from the Maxwellian cannot introduce substantial changes in the result. It follows from inequality (3) that:

Из неравенства (3) можно получить условие на абсолютную плотность возбужденных атомов в газе "b," считая отношение N_1^b/N_3^b внешним параметром, то есть эффективную температуру возбуждеяиня атомов газа "b" заданной. Для простоты мы будем считать распределение электронов по энергиям максвелловским с температурой T и поскольку средняя энергия электронов имеет значение, сравнимое по величине с энергией возбуждения атомов, отличие функции распределения от максвелловской не может внести существенных изменений в результат. Из неравенства (3) следует:

$$\frac{\theta_{13}}{t_{ba}} \gtrless \frac{\left[\exp\left(\frac{E_3 - E_2}{kT}\right)\right]\left(\frac{\theta_{31}}{\theta_3} + \frac{\theta_{21}}{\tau_2}\right) - 1 + \theta_{21}\left(\frac{1}{\tau_{32}} + \frac{1}{\theta_{32}} - \frac{1}{\tau_{21}}\right)}{1 - \frac{N_1^b}{N_3^b}\left[\exp\left(-\frac{E_2}{kT}\right)\right] + \theta_{21}\left(\frac{1}{\tau_{21}} - \frac{1}{\tau_{32}} - \frac{1}{\theta_{32}}\right)}, \tag{4}$$

The $>$ or $<$ signs refer to cases where the denominator on the right is positive, or negative, respectively.

The quantities θ_{31}/θ_3 and θ_{21}/θ_{32} do not depend on the density of the electrons in the discharge, but are determined by the cross sections of the corresponding processes and by the temperature of the electrons.

Inequality (4) has a different meaning in different regions of the variables $\theta_{21}(1/\tau_{21} - 1/\tau_{32})$ and θ_{31}/τ_3. The range of these variables is divided by two curves into four regions, the equations of which are obtained by equating the numerator and the denominator to zero:

Знак $>$ или $<$ относится к случаю, когда знаменатель справа положителен или отрицателен.

Входящие в эту формулу величины θ_{31}/θ_3 и $\theta_{21}/_{32}$ не зависят от плотности электронов в разряде, а опредедяются сечением соответствующих процессов и температурой электронов.

Неравенство (4) имеет различный смысл в разных областях изменения переменных $\theta_{21}(1/\tau_{21} - 1/\tau_{32})$ и θ_{31}/τ_3. Область изменения переменных $\theta_{21}(1/\tau_{21} - 1/\tau_{32})$ и θ_{31}/τ_3 разделена на четыре части двумя кривыми, уравнения которых определяются обращением в нолв числителя и знаменителя правой части (4).

1. $$\theta_{21}\left(\frac{1}{\tau_{21}} - \frac{1}{\tau_{32}}\right) = \frac{N_1^b}{N_3^b}\exp\left(-\frac{E_2}{kT}\right) - 1 + \frac{\theta_{21}}{\theta_{32}},$$

2. $$\frac{\theta_{31}}{\tau_3} = \frac{\theta_{21}(1/\tau_{21} - 1/\tau_{32} - 1/\theta_{32}) - (\theta_{31}/\theta_3)\exp\left[(E_3 - E_2)/kT\right] + 1}{\exp\left[(E_3 - E_2)/kT\right]}.$$

To first order, the rate $1/\theta_{32}$ can be neglected in comparison with $1/\tau_{32}$, and the assumption can be made that $\theta_{31}/\theta_3 \approx 1$; then the curves mentioned above become straight lines described by the equations (see figure):

В первом приближении можно пренебречь вероятностью $1/\theta_{32}$ по сравнению с $1/\tau_{32}$ и положить $\theta_{31}/\theta_3 \approx 1$, тогда указанные кривые перейдут в прямые линии, описываемые следующими уравнениями (см. рисунок):

1a. $$\theta_{21}\left(\frac{1}{\tau_{21}} - \frac{1}{\tau_{32}}\right) = \frac{N_1^b}{N_3^b}\exp\left(-\frac{E_2}{kT}\right) - 1,$$

2a. $$\frac{\theta_{31}}{\tau_3} = \frac{\theta_{21}(1/\tau_{21} - 1/\tau_{32}) + 1 - \exp\left[(E_3 - E_2)/kT\right]}{\exp\left[(E_3 - E_2)/kT\right]}.$$

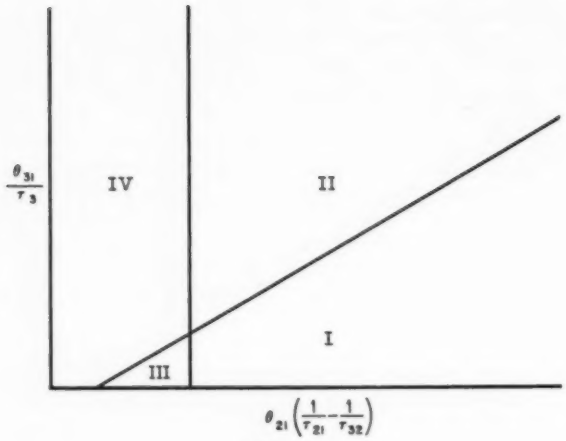

Fig. 1

Region I corresponds to the formation of a population inversion in gas "a" even in the absence of gas "b" (similarly as in refs. 1 and 2). In region II, the population inversion occurs because of the presence of gas "b." In region III, gas "b" prevents the formation of a population inversion. The occurrence of a population inversion in region IV is impossible.

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Область I соответствует условиям, когда в газе "a" возникает отрицательная температура даже при отсутствии газа "b" (аналогично 1 и 2). В области II отрицательная температура возникает благодаря присутствию газа "b." В области III газ "b" мешает установлению отрицательной температуры, которая имеет место при его отсутствии. В области IY состояния с отрицательной температурой получено зите не можем.

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Participants in the Vienna WMO August 1961 meeting including Jacquiline Lenoble *Lille,* K. Ya. Kondratiev *Leningrad,* I. Galanina *Moscow,* and N. Untersteiner *Vienna*

Optics in the Netherlands

A. C. S. Van Heel

Applied optical research is of course carried out in the Netherlands as in any country where physical research is performed. In recent times this has been proved clearly by Zernike in Groningen. The number of his disciples, however, has not been large and the main trend of research in Groningen lies in another direction.

We may mention M. Bottema who worked on scattering by imperfect gratings, both in the U.S.A. and in the Netherlands. Together with J. W. Kuiper, the same author will soon publish an article on the optics of a so-called superposition eye, like that of insects and some locusts, which can adapt itself to low levels of brightness.

A research group under the direction of R. Brinkman is occupied with the study of linear and toroidic pinch-discharges, in which conventional optical apparatus, like vacuum spectrometers, is being used.

A special feature of the Zeeman laboratory in Amsterdam (director, J. C. Kluyver) is the way in which the distance of spectral lines on a photographic plate is measured. The spectral line is scanned by means of an octagonal mirror and a photomultiplier, and the result is displayed on an oscilloscope screen. The synchronous current, feeding the motor, is also used to establish the time-base, thereby ascertaining very accurately the maximum of the line. It is hoped to measure the position of the plate interferometrically with an automatic fringe-counting device, and to transmit the data directly to a computer; this hope has not yet been realized however.

Another subject that is being studied in this laboratory is the measurement of absorption in the ultraviolet in an atomic beam by means of a Fabry-Perot interferometer mounted in a vacuum. Changes in the position of the rings are artificially produced by admitting small amounts of gas. The position of the rings, as well as the pressures, are plotted against time.

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The structure of spark discharges of about 100 μsec duration is studied by throwing an image of the spark on the slit of a monochromator by means of a rotating mirror. The same mirror actuates a photoelectric cell connected to the grid of a thyratron, which in turn triggers the spark discharge.

A spectrometer of the Jacquinot type will be set up and a 6-meter vacuum spectrometer for the study of the spectra of rare earths and actinides is under construction.

Knowledge of reflection coefficients in the ultraviolet is important for all work in this region. Research is going on to determine this property and also the thickness of evaporated layers during evaporation.

The absorption of Ba light by Ba^+ ions in an atomic beam and the double resonance effect is also being studied.

Optical work in the Koninklijke/Shell-Laboratorium, Amsterdam comprises among other projects the development of a method for observing reflection spectra in the infrared by means of the attenuation of total reflection at the interface between a strongly refracting dielectric and an absorbing sample. In the case of a nonabsorbing sample, total reflection will occur when the angle of incidence is somewhat larger than the critical angle. In the wavelength regions where there is absorption, however, there is less reflection. In this way it appears feasible to obtain a reflection spectrum of high contrast and intensity, strongly resembling a transmission spectrum. These spectra may be used not only for analytical purposes, but also to provide the wavelength dependence of the optical constants n and κ. It should be added that the dielectric (AgCl) may be given such a form that more than one reflection occurs, thereby enhancing the intensity of the peaks in the absorption curve.

Another project is the construction of an apparatus for measuring the scattering of light in colloidal solutions and its angular dependence. A photometer measures the flux of light emitted by a well-defined volume of liquid within a well-defined angle. The intensity of the scattered light is compared to part of the primary beam

in a compensator with a sensitive null-amplifier. (The Rayleigh factor R has been determined with a precision of 2.5%.) The value of Avogadro's number, calculated from the results with some pure liquids with the aid of the Einstein formula, shows the reliability and accuracy of the instrument for absolute light-scattering measurements. In this connection it might be mentioned that the dependence of the refractive index of liquids on pressure is also being studied in the Shell Laboratories, in the range of 0 to 1 atm by means of a Rayleigh interferometer. It need not be stressed that the application of many standard optical methods in this laboratory is extensive.

In different departments of the Physical Laboratory at Philips, Eindhoven, optical work is being carried out on various problems, mostly in connection with the modern electronic and lighting industry and lying therefore in the border regions of optics. There is, however, a specialized optical group doing much work on the application and adaptation of known optical methods to the new problems they encounter. As it is not feasible to enumerate the many fields in which research is being done, we can only cite a few examples:

A television set may be described as an electronic telescope, but much optics of the usual type is also necessary. Small wonder that the group is busy with the measurement of the response function of television camera lenses and of the influence of beam splitters on the image quality of color television cameras! Another activity concerns television projection, including Schmidt systems and eidophors, and the precision measurement of displacements by means of optical gratings. This latter is done in such a way that signals produced are directly usable for automatic control of an electronically guided mechanical tool.

It is obvious that light sources are studied here. Examples are: sodium lamps with infrared-reflecting and light-transmitting mantles; selective temperature radiators; electroluminescence in GaP and SiC. Also investigations of the fluorescence of solids and the behavior of gas discharges are being carried out and the results are applied in the fields of electronics and optics.

Contacts between electronics and optics are manifold. Electronmicroscopy is not the only link; the formation of images in cathode-ray tubes is also being studied, especially in image tubes for color television. Optoelectronics is a new field, where light plays a part as an element in electric circuits, and where photoresistors, light amplifiers, and masers are important subjects of research.

Radio waves of 2 mm form a special subject of study, the mathematical treatment of diffraction and propagation of radio waves in the atmosphere having interesting features in common with optics.

In studying semiconductors, many optical methods are used, e.g., the detection of the regions of magnetization by means of magneto-rotation and the study of the surface of solids by means of total reflection. Of course measurements of absorption and reflection in the ultraviolet and infrared, and specialized spectroscopic analyses, are extensively carried out.

A fine piece of research on anomalous x-ray transmission of perfect single crystals of germanium and silicon might also be mentioned to show how far and how vague is the border of optics in the research program of this laboratory.

Another feature deserves attention: the tremendous expansion of the use of optical instruments in workshop and factory. For a mechanic in a transistor factory, a binocular microscope is an indispensible tool, though it must be added that it usually is built as a laboratory instrument.

The many problems in illumination are closely related to the science of vision. Neither street lighting nor the lighting of airports or tunnels or workshops can be studied without a deep knowledge of physiological optics. There is a close connection in this field between the Philips Laboratory and the Institute of Perception Research in Eindhoven, a new foundation under the direction of J. F. Schouten, and closely related to the recently founded Technological University of Eindhoven.

Another Institute in the Netherlands, where physiological optics is being studied, is the Institute for Physiology of the Senses at Soesterberg, working under the National Defense Council of the Netherlands. Its director, M. A. Bouman, is a well-known-worker in this field, some of whose many publications have appeared in *J. Opt. Soc. Am.*

The spectroscopic work of Ornstein and his school in Utrecht is being continued by a new group of workers under the direction of J. A. Smit, whose principal aims are the study of light emission of gases at high temperatures, including the study of high-temperature furnaces and of electrical gas discharges. On the one hand, the production of high temperatures is a subject in itself; on the other hand, the understanding of the mechanism of light emission in furnaces and in gas discharges is of great importance, not in the least for the improvement of light sources for spectrochemical analysis. The measurement of transition probabilities and of excitation functions is also taken up. One of the main subjects has been, and still is, the investigation of the flame as a standard of temperature. Comparison with a tungsten band lamp by means of the observation of the reversal of emission lines, e.g., the sodium lines, proved the possibility of using flames as temperature standards. Fundamental research into the fluorescence yield and of the collision probabilities was necessary to allow numerical conclusions to be drawn.

Spectrochemical analysis by the flame method led to the construction of a flame photometer with a photo-

electric detector, and a mass spectrometer has been adapted to analyze flame gases.

Arc discharges were studied to determine transition probabilities, while the properties of the continuous spectrum of a carbon arc were also explored. The excitation functions of atoms in a low-pressure arc have been studied by means of modern experimental aids, such as were not available to L. S. Ornstein before the Forties. Improvements in photoelectric methods have been largely due to J. M. W. Milatz, and the flame-photometry work has been activated by C. T. J. Alkemade. Recently, the study of the mechanism of gas discharges has led to concrete results concerning the production of band spectra.

In the research and development sections of the optical firm "De Oude Delft" an important subject is the mirror system with concentric corrector, originally devised by its president, A. Bouwers. Two important new features are the conical lens and the plate for color correction. With the first a considerable part of the residual aberrations of a system consisting of a spherical mirror plus one or more concentric meniscus lenses is removed. This lens is mounted at the center of curvature of the system, and it has the form of a nearly plane-parallel plate of which one surface has the form of an almost flat cone. The production of this lens is considerably simpler than that of the original corrector plate of Schmidt.

The color correcting plate is often combined with the conical lens. It consists of a plane plate composed of a plano-convex and a plano-concave part cemented together. The materials of the two components have practically the same refractive index but different dispersions. Thus the chromatic aberration introduced by the concentric meniscus is corrected, while the system still satisfies the sine condition.

The development of concentric systems for photographing fluorescent screens and similar objects has led to nine types of x-ray cameras with focal lengths ranging from 150 to 210 mm, fields from 63 × 63 to 90 × 90 mm², magnifications from 1/6.3 to 1/4 and numerical apertures from 0.69 to 0.74.

Telecameras with reduced length have been constructed, e.g., a camera with a focal length of 5 meters and an overall length of only 1.3 meters.

A range of high-altitude aerial cameras has been developed in which the combination of high resolution and high luminosity of the catadioptric optical system as described above is realized. This permits the use of fine-grain high-resolution film resulting in a high information content of the image, even with comparatively short focal lengths of the optical system. We can cite as an example a camera with a focal length of 30 cm, resolving on medium fine grain emulsion 45 line pairs/mm over the whole field of 57 × 57 mm², when the object has a log contrast of only 0.2.

Aerial cameras for extremely low altitudes, using refractive optical systems of high apertures (1:1.1 to 1:1.6), have been designed and built, in which the blur due to the image motion is eliminated. For this purpose a special shutter has been constructed permitting exposure times down to 1/15000 sec.

The infrared is another important field of activity of "De Oude Delft."

Replacement of the concentric meniscus by a pseudo-concentric system entails a favorable reduction of the dimensions of the spherical mirror, while the sine rule is still satisfied. A slight reduction of aperture is then necessary, however.

A good application of anamorphotic systems is the rectification of the horizon in scenes projected in cinema theaters on a curved screen. This can be done by the use of a mirror system in which the light rays are incident under a certain angle. By adding a pair of small prisms, or by combining the cylindrical concave and convex reflecting surfaces on a single piece of glass, an additional degree of freedom is gained. A somewhat similar procedure may be applied to camera objective lenses, when a curved horizon has to be straightened.

The study of concentric lens systems led to the construction of a horizon camera with a field of 355° × 15°.

The field of mirror systems also comprises microscope objectives. Apochromatic systems with a flat field, e.g. 40 ×, n.a. 0.65 and 100 ×, n.a. 1.3 and also a system for the ultraviolet 300 ×, n.a. 0.85, have been successfully developed by filling the space between the two mirrors with glass or quartz.

A light amplifier has been constructed by this company, producing easily observable images of objects with very low brightness down to below 10^{-6} ft-L. It allows the taking of scenes with a movie camera when the object is illuminated only by the moon. A special feature is that it is possible, by changing the tension on the electrodes, to influence the magnification, which is of special importance when the apparatus is used for amplifying the brightness of x-ray screens. Amplification of lumens is 100; thus at a magnification of 1/5.2 the brightness is increased about 3000 times.

We shall conclude our report of the activities of this optical firm with one more novelty: An observer, while looking through the two eyepieces of a scanning stereoscope, gets the impression of flying over the whole field of an aerial photograph, just by turning two knobs, which at the same time give the x and y coordinates.

Special designs of aerial cameras have been made for photography from high altitudes, with the same desired quality of the images, by correcting the effects of changes of temperature and pressure. In connection with these high exigencies, specialized apparatus has been constructed to measure currently the frequency response of the systems. Automatic focusing of a cam-

era has been made possible by the use of a "noise" plate, rotating in the image plane. If the image is sharp in the plane of this plate, the noise on a photocell behind it will be maximal.

In the Technical Physics Laboratory of the Technological University at Delft much of the optical work is concentrated in the Optics Section, though other sections too have optical interests. That section under the direction of J. B. Westerdijk has, among other work, constructed a grating spectrometer for the far infrared between 50 and 1000 μ. The gratings have grating constants ranging from 0.15 to 3 mm, the aperture is 1:1, and the focal length of the parabolic mirror is 30 cm. Work is going on to improve the different detector systems, and to produce dipole radiation in this region. Studies are also in progress on the measurement of transmission and reflection of materials for the use in the spectrometer, the construction of waveguides to improve illumination of the entrance slit (now illuminated by an elliptical mirror), and the making of gratings of such a construction that the disturbing radiation of smaller wavelength is eliminated.

In the X-Ray Section, under the direction of P. M. de Wolff, the diffraction patterns produced by regular series of holes in a metal template illuminated by a parallel pencil of monochromatic light are being studied in order to obtain the optical analogs of diffraction patterns produced by molecules, or rather regular sets of molecules, in the x-ray region. The length of the usual setup with lenses is diminished by using mirrors instead of lenses.

J. B. Le Poole has resumed his researches in the field of electron optics, after some years of work in another area.

In B. S. Blaisse's group, the work on low-temperature physics has an optical experiment under way, viz., the measurement of expansion coefficients at temperatures around 4°K, and for this purpose an interferometer of special design is being built: A cell is formed by two plane-parallel plates spaced by the sample. Light reflected from the front plate and from the back plate is brought to interfere, and changes in the length of the spacing with temperature changes are made observable. In order to enhance the sensitivity, a quarter-wave plate is mounted between the two plates while the incident light is plane-polarized, observation by means of a photocell taking place with an analyzer. The position of the fringes is measured by influencing the phase difference between the two components by an ADP crystal before the first plate. A sinusoidal shifting of the lines is produced by a sine signal on the ADP crystal, while, at the same time, a pressure scanning in the cell has to be applied. This last, however, is not feasible at helium temperatures and therefore a second similar cell is placed in the room, the light passing through both cells. Moreover, the presence of the second cell has the advantage that the light path is compensated, and white light may be used. Sensitivity is of the order of $\lambda/100000$.

In the Optics Section, directed by the author, much time has been given to optical design and more especially to the methods of T. Smith. Optical systems have been conceived, executed, and tested, e.g., the optical part of a wide-angle camera with a field of 260°, and a horizon camera giving, in a single exposure, a picture of 90% of the horizon and a vertical field of 20°. An apochromatic collimator is under construction, using modern glasses. Its aberrations are below $\lambda/4$ for the whole visible spectrum with an aperture 1:12.5 and a focal length of 1 meter. Systems are designed, chiefly for educational purposes, that show several of the aberrations in a pure form: e.g., coma, distortion, lateral chromatic aberration without axial chromatic aberration, etc.

Of the experimental work the development of alignment methods should be mentioned. For precision work it proved of importance to obviate the use of lenses as far as possible. Spheres and concave and plane mirrors have given better results. Moreover, they are easier to handle in practical applications. Spherical aberration and diffraction, when well drilled, prove to be helpful instead of a hindrance. A precision of 0.2 sec of arc may be readily attained at distances from under 1 meter to well over 40 meters. Progress is being made in the testing of the flatness of surfaces with the same precision and for the same range of distances. A sphere with a cap of the same very homogeneous glass is provided on the outside of the aluminized cap with a scratch long enough to give light in a, say, horizontal plane over a range of 90°. Spherical aberration and diffraction produce a pattern consisting of a series of horizontal lines. By means of some auxiliary pieces, the flatness of the surface thus defined can be ensured to lie within the said limit. Brightness is so intense that it is easy to find the pattern even in daylight. As the pattern stretches over a wide horizontal range, it is easy to locate. By adding transverse scratches, even the straightness of lines is thus easier to test.

Determining the optical thickness of coatings is another line of research. By adapting Françon's idea of using Savart plates and by making use of photometric settings instead of observation of the interference fringes, it proved possible with a specially designed apparatus to attain a precision of $\lambda/1000$. Work on adapting this method to observation inside the evaporating dome is in progress.

In the same Laboratory for Technical Physics at Delft is housed the Optical Department of the T.P.D., a research organization based on the cooperation of the Technological University at Delft and the Organization of Applied Scientific Research (T.N.O.). Of the many problems considered there, we mention the following:

Technical applications of the results of the research

on alignment were used in the determination of the amplitude of swaying church towers, especially during repair, mostly by the now old but simple method with zone plates. Amplitudes of 1 mm at heights of 50 meters were observed with a precision of a few tenths of a millimeter, a limit set by atmospheric disturbances; the usual geodetic instruments failed on account of the trepidations in the surrounding soft soil. The sagging under load of experimental runways at the Schiphol airport was determined, and the desired precision of 0.02 mm at 40 meters on nine tracks simultaneously was reached throughout the whole range of experiments over a period of some months. This was very helpful in checking the calculations on stiffness of the cement layers. Tasks such as mounting sixty axes of a large machine parallel to one another were fulfilled in a satisfactory way without undue loss of time.

Of the several optical instruments being developed for special purposes we shall mention a novel form of polarimeter cell of double conical shape (in order to minimize sample liquid) and an absorption cell for the determination of feeble absorptions of limited quantities of liquid. In the last case we might speak of optical amplification: a light beam is sent many times through the sample and each time only a small fraction of the beam is tapped off. The sum of all these fractions is affected by absorption about ten times more than by a single passage through the sample. The tapping off of the light fluxes is achieved by means of frustrated total reflection.

Recently a prototype of a device was finished for viewing the inner wall of straight pipes and tubes with an internal diameter of a few centimeters and a length of up to several tens of meters. The whole of one section of about 1 cm length (calculated along the direction of the tube axis) can be observed in one glance, while the sections are made visible one after another by running along the axis of the tube one of the two rotating prisms that enable the observer to see the image.

The special cameras mentioned above under the heading of the Technological University have been developed and built here. A computer of their construction was adapted for ray tracing. In recent times more and more designing and ray tracing is being done on modern electronic computers. Programming of optical calculations on these computers is entrusted to part of the T.P.D. staff.

photo BEN-ZVI

Participants in the Spectral Line Shape and Molecular Interactions Symposium held in Israel in August 1961; see report on page 377.

Optics in India: The Spectroscopic Behavior of Rock Salt

C. V. Raman

The origin of the infrared activity of rock salt is discussed in terms of the free vibrations of the crystal. Experimental data on the Reststrahlen frequencies and on the frequency displacements of scattered radiation are used to explain the spectroscopic behavior of rock salt in the near infrared.

Rock salt was one of the first minerals of which the crystal structure was established by x-ray analysis. Its structure may be described in simple terms as made up of two interpenetrating lattices, each composed of atoms of one kind. The sodium atoms in one lattice are surrounded by six chlorine atoms in the other lattice and vice versa, in such manner that the grouping exhibits cubic symmetry. The sodium and chlorine atoms appear interspersed with each other in the cubic planes of the structure, while in the octahedral planes they appear separately in alternate layers.

The transparency of rock salt over a wide spectral range extending from 0.2 μ to 10 μ makes it a material of first-rate importance in applied optics and especially for use as dispersing prisms in the infrared. The dispersive power of rock salt is very low, between 1 μ and 5 μ, but improves at greater wavlengths. On the other hand, the absorption which is negligible at 10 μ becomes sensible at 13 μ and increases rapidly beyond 15 μ. Hence, rock salt may best be used as a prism material for infrared spectroscopy between 7 μ and 14 μ. It ceases to be useful beyond 15 μ.

It is well known that rock salt exhibits, in the region of long wavelengths, a high reflecting power which reaches its maximum value of about 90% at 54 μ. The strength of this reflection falls off rapidly at shorter wavelengths and is negligibly small for all wavelengths less than 33 μ. The fall is less rapid for wavelengths greater than 54 μ and the reflecting power reaches a limiting value of about 20% at 100 μ. These facts call for explanation; in particular, it may be asked why, at 15 μ which is outside the spectral region of strong reflections, the absorbing power is nevertheless large enough to impair the usefulness of the material for infrared spectroscopy.

It is proposed in this paper to review briefly the contents of a memoir by the author which has been recently published and in which the spectroscopic behavior of rock salt has been discussed in detail.[1]

The Free Vibrations of the Structure

The dispersion, absorption, and reflection of infrared radiation by a crystal are effects arising from the interaction of the electromagnetic field in the radiation with the structural units composing the crystal. As a first step toward an understanding of these effects, it is necessary to consider the nature of the spectrum of the free or spontaneous vibrations of these structural units. We may deduce their modes and frequencies by the methods of classical mechanics. For this purpose, the atomic nuclei may be regarded as simple mass particles and the electronic clouds surrounding them as massless springs which hold the structure together. The relevant theory is fully set out in the memoir cited above and it is sufficient here to state the results to which it leads.

It emerges that the vibrational mode of highest frequency of the rock salt structure is one in which the atoms of sodium and chlorine oscillate against each other in opposite phases. Eight other modes of free vibration are also possible. They may be described simply in terms of the crystal structure: four of the modes are oscillations of the cubic layers, while the other four modes are oscillations of the octahedral layers, the movement alternating in phase from layer to layer, and being either normal or tangential to those layers. Since the oscillations of the sodium and

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chlorine atoms may be either in the same phase or in opposite phases, we have four modes for the cubic layers and four modes for the octahedral layers, and hence eight in all. The oscillations of the sodium and chlorine atoms located in the same cubic layers would be coupled with each other. But the oscillations of the sodium and chlorine atoms, appearing as distinct layers in the octahedral planes, would be independent.

The Origin of Infrared Activity

We next proceed to consider the relation between the free vibrations of the structure of the crystal and the effects arising from the passage of infrared radiation through it. The electric field in the incident radiation acts both on the positively charged nuclei and on the negatively charged electrons. But in all the modes of vibration with which we are concerned, there are as many positively charged nuclei moving in one phase as there are others moving in the opposite phase. It can be shown that, as a consequence, the displacements of positive charge when totaled up cancel out in all the modes under consideration. Hence, the free vibrations of the structure cannot be excited by the forces exerted by the field on the atomic nuclei. Necessarily, therefore, the movements of the atomic nuclei can have no effect on the radiation passing through the crystal. We conclude that the infrared activity of the crystal arises solely by reason of the forces exerted by the field on the negatively charged electrons and of the resulting movements; such activity is only possible when the displacements of negative charge produced do not cancel out when summed up over each structural unit.

Since the electrons are held in position by their interactions with each other and with the positively-charged nuclei, the displacements of negative charge induced by the field would necessarily disturb the nuclei from their positions of equilibrium. But the nuclear movements thus arising would not contribute to the infrared activity. Thus, while in the free vibrations of the structure, the massive, positively charged nuclei play the leading role and the electrons a subsidiary one, the situation is reversed in respect of the infrared activity, the electrons here playing the leading role and the nuclei a subsidiary one. In other words, the spectrum of free vibrations and the spectrum of infrared absorption are essentially different in their nature and origin. Both being properties of the same structure, we may expect to find some resemblances, but nothing in the nature of an identity or complete correspondence is to be expected.

The Reststrahlen Reflections

The considerations set forth above indicate that the mode of vibration in which the sodium and the chlorine atoms oscillate in opposite phases would be that exhibiting by far the strongest infrared activity. Their approach and recession would be accompanied by a periodic movement of the electronic cloud located between each pair of nuclei. The effects due to the displacements of electric charge in the successive cells of the structure would be additive and would thereby attain a large magnitude. Indeed, the activity may be expected to be so great that secondary radiations would emerge from the units of the structure along the external boundary of the crystal and conspire to give a powerful surface reflection. There would also be a strong absorption and extinction of the radiation actually penetrating into the crystal.

As a matter of actual observation, the surface reflection appears with great strength between 50 μ and 60 μ, its maximum of intensity being at 54 μ. On the other hand, the minimum of transmission by very thin films of rock salt appears at about 60 μ, being thus displaced a little further into the infrared. In what follows, we shall take 56 μ to be the wavelength corresponding to the frequency of the strongly active mode of free vibration of the rock salt structure.

Infrared Activity of Higher Orders

The absorption of infrared radiation arises when the electromagnetic energy of the field is taken up and transformed into vibrational energy in the crystal. When the frequencies of the field and the mechanical vibration are identical, a quantum of radiational energy changes over to a quantum of vibrational energy. There are also other possibilities: the energy of the radiation taken up by the crystal may appear as two, three, or a larger number of quanta of vibrational energy. Thus, we are led to expect, besides the intense absorption around 56 μ, a series of other absorptions around 28 μ, 19 μ, and 14 μ, respectively. They may be referred to as the absorptions of the second, third, and fourth orders, respectively. The possibility of observing the higher orders of absorption arises by reason of the first-order absorption being itself of great strength. The absorptions of higher order would necessarily be weaker and of progressively diminishing strength with increasing order. Nevertheless, when the absorption path is sufficiently increased, their effect on the transmission should be observable.

That the lack of transparency of rock salt at wavelengths greater than 15 μ, which renders it unusable as material for dispersing prisms, is due to these absorptions of higher order may be inferred from the observed facts of the case. The absorption at 14 μ is noticeable when the thickness of the plate is 5 cm or more, but it ceases to be significant when the absorption path is reduced to 3 cm or less. Yet in this range of thickness, there is a complete cutoff of the incident

radiation commencing at 19 μ and extending to greater wavelengths. Reducing the thickness to 15 mm produces but little observable change in this behavior, the wavelength of cutoff drifting slightly to 20 μ. Not until the thickness is reduced to 1 mm or so does the transmission at 19 μ become at all comparable with that observed at 14 μ with far larger thicknesses. To obtain such a free transmission at 28 μ, the path has to be further reduced to about 50 μ, while only films which are a few microns thick would give an observable transmission at 56 μ. It is evident from such facts that we are dealing with absorptions of altogether different orders of magnitude in these four cases.

The Infrared Activity of the Other Modes

We have now to consider the eight other modes of free vibration mentioned earlier. By reason of the vibrations being in opposite phases in the alternate layers, the displacements of electric charge in all the eight modes cancel out in the *first* approximation. But in the case of the four coupled oscillations of the sodium and chlorine atoms appearing in the cubic layers, the displacements of electric charge do not cancel out in the *second* approximation; there is a surviving component having twice the frequency of the mode under consideration. Hence these coupled vibrations would be strongly infrared active, but with doubled frequency in each case.

Taking 56 μ as the wavelength of maximum infrared activity, the wavelengths corresponding to the four modes referred to may be theoretically estimated to be 66 μ, 78 μ, 90 μ, and 108 μ, respectively. The halved wavelengths at which their second-order activity would manifest itself would therefore be 33 μ, 39 μ, 45 μ, and 54 μ, respectively.

The foregoing figures enable us to understand why the spectral region in which the strong surface reflections appear extends toward shorter wavelengths up to 33 μ and terminates at that wavelength. This extension is clearly the result of the superposition of the effects due to these modes and that of the mode of greatest activity. The activities of these modes appearing at 33 μ, 39 μ, 45 μ, and 54 μ are likewise responsible for the features noticeable in the spectral transmission curves of thin plates and thin films of rock salt at these wavelengths. These features have been observed and reported by Mentzel and by Barnes and Czerny in their studies on the infrared behavior of rock salt.

By reason of their symmetry properties, the vibrations of the sodium and chlorine atoms appearing in the layers parallel to the octahedral planes can exhibit no infrared activity. They, and indeed all the other modes as well, are accessible to observation by other spectroscopic methods. In this way, all the nine characteristic wavelengths of rock salt can be determined: viz., 56 μ, 59 μ, 64 μ, 66 μ, 71 μ, 78 μ, 85 μ, 90 μ, and 108 μ. These wavelengths form a nearly continuous sequence extending into the region of great wavelengths far beyond that at which the maximum intensity of surface reflection appears. We are thereby enabled to understand why the spectral region, in which strong surface reflections appear, extends up to 100 μ. An intense excitation of the electrons in a thin layer adjacent to the surface of the crystal must of necessity involve all the nine possible modes of vibration and not only that of the mode of highest frequency. The strength of the excitation of any particular mode would be determined by the difference between its frequency and that of the most highly active mode. It would, therefore, fall off steadily as we recede from the mode having the highest activity towards lower frequencies and longer wavelengths.

The Spectrum of Light Scattering

The picture of the dynamical behavior of the rock salt structure and its relation to the infrared behavior of the crystal briefly summarized above finds a striking confirmation in the results of two other entirely independent lines of research. The first is the evaluation of the thermal energy of rock salt over the whole range of temperatures extending from absolute zero upwards, the theoretically determined and spectroscopically confirmed frequencies of vibration of the structure and their respective degeneracies being the basis of the calculation. To enter into this subject would take us beyond the field of applied optics; we shall therefore here only deal with the other line of investigation. This is a spectroscopic method closely related to the field of infrared studies, viz., the study of the spectral shifts observed in the scattering of monochromatic light in its passage through rock salt.

The frequency shifts observed in the scattering of light arise from the periodic changes in the optical scattering power of the structural units in the crystal. These changes are produced by their internal vibrations and hence the observed shifts may usually be identified with the frequencies of the vibrations. But in a particular class of cases, frequency shifts are recorded with notable intensity in the spectrum of the scattered light, which are double the frequency of the vibrations of the structure. The frequency shifts observed with rock salt are all of this kind, and the reason for this is not far to seek: In each of the nine modes of free vibration, we find a sodium atom approaching a chlorine atom on one side and simultaneously receding from a chlorine atom on the other side, and vice versa. The increased scattering power due to the approach is set off by the decrease due to the recession and cancels out in the *first* approximation. But in the *second* approximation, there is a residue left over, and this

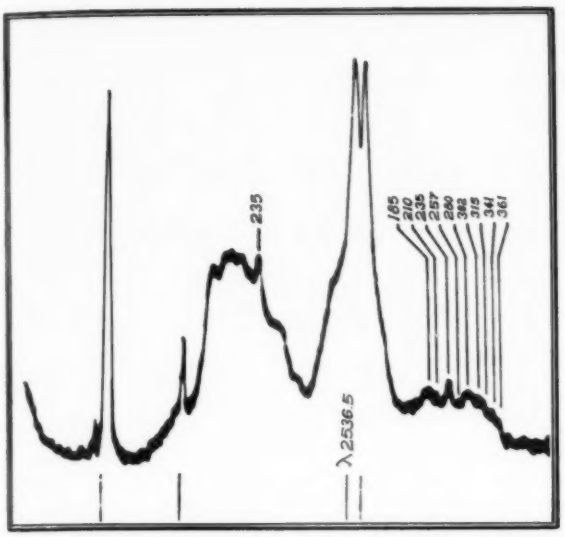

Fig. 1. Rasetti's microphotometer record of the rock salt spectrum.

would evidently be periodic but with a doubled frequency.

The spectrum of the scattering of light in rock salt was successfully recorded several years ago by Rasetti in a noteworthy investigation. The microphotometer record of the spectrum obtained by him is reproduced from his paper as Fig. 1. The frequency shifts in wavenumbers have been marked in the figure. The record shows the position of the exciting radiation (2536.5 Å) from a water-cooled mercury arc enclosed in quartz which was placed between the poles of an electromagnet in order to eliminate the self-reversal of the emitted radiation. The frequency shifts were both negative and positive, and they appeared respectively to the left and to the right of the position of the exciting radiation in the microphotometer trace.

The negative shifts are recorded with great intensity and, being overexposed in the original spectrogram, are not so clearly resolved from each other in its microphotometer trace as the positive shifts. These latter appear as successive steps in the record, and the respective frequency shifts are easily read off from their displacements with respect to the λ 2536.5 line. It will be seen that all the nine different frequency shifts may be clearly recognized. Their values as read off from the record on the right-hand side are in excellent agreement with the doubled frequencies of the respective modes, as theoretically estimated.

The relative intensities of the nine negative-frequency shifts as indicated by Rasetti's microphotometer record are also in satisfactory accord with the estimates based on the nature of the individual modes and their respective degeneracies. It should be mentioned the frequency shifts of ± 235 cm^{-1} stand out in Rasetti's original spectrogram as sharply defined lines. They represent the doubled frequency of vibration of the chlorine atoms located in the octahedral layers in which the movements are parallel to these layers. The notable intensity of the 235 cm^{-1} line is a consequence of the eightfold degeneracy of the mode.

Reference

1. C. V. Raman, Proc. Indian Acad. Sci. Sec. A **54**, 253–304 (1961).

Meetings Calendar

1962
May

—	IRE International Scientific Radio Union, Washington, D.C., Spring Meeting *IRE, 1 E. 79th St., New York 21, N.Y.*
2	OSA President MacAdam's address to S. Calif. Section on Optical Engineering, Los Angeles, Calif.
3	OSA President MacAdam's address on Optical Engineering to Sigma Xi Club, San Diego, Calif.
6–10	French Society of Ophthalmology Congress, Paris *Secrétaire Général Société Francaise d'Ophthalmologie, 27 rue du Faubourg-Saint-Jacques, Paris, France*
6–10	Electrochemical Society Meeting, Statler Hilton Hotel, Los Angeles, Calif.
7–11	Society of Photographic Scientists and Engineers, Somerset Hotel, Boston, Mass. *K. Kohlman, 13712 Mariana Dr., Rockville, Md.*
8	OSA Rochester Section Annual Dinner Meeting *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*
8	Society for Applied Spectroscopy New York and Philadelphia Sections Solid State Lasers Meeting
14–16	14th Annual National Aerospace Electronics Conf., Biltmore Hotel, Dayton, Ohio *G. Langston, 4745 Rean Meadow Drive, Dayton 40, Ohio*
14–16	Symp. on Thermionic Power Conversion, Colorado Springs *V. C. Wilson, GE Company, Research Lab, Schenectady, N.Y.*
20–23	Radiation Research Society 10th Annual Meeting, Colorado Springs
21–25	Max Planck Institute for the Advancement of Science, 13th General Assembly, Düsseldorf *J. Ammundsen, Sammenslutningen of Arbejdsgivere Indenfor den Keramiske Industri, Norrevolgade 34, Copenhagen, Denmark*
23	OSA President MacAdam's address to First Meeting Wash. D.C. Section on Color in Court.
22–24	IRE National Microwave Theory and Techniques Symposium, Boulder, Colo. *R. W. Beatty, NBS, Boulder, Colo.*
28–30	American Ophthalmological Soc., Hot Springs, Va.
28–June 2	International Optical League Berlin Congress *G. H. Giles, IOL, 65 Brook St., London, W.1, England*
28–June 3	German Bunsen Society for Physical Chemistry 61st General Assembly, Münster, Germany *Carl Bosch Haus, Varrentrappstr. 40–42, Frankfurt am Main, Germany*
29–June 19	World Meteorological Organization Congress, Geneva, Switzerland

31–June 7 International Television Conference, London *Institution of Electrical Engineers, Savoy Place, London, W.C.2, England*

late Interphoto Congress, Copenhagen *International Photography and Cinematography Dealers Association, Steienvorstadt 63, Basel 10, Switzerland*

late Washington Symposium on Use of Artificial Satellites for Geodetic Purposes *International Association of Geodesy, 18 rue Auber, Paris IX, France*

late Journées de la Lumière, Grenoble *W. Bing, Assoc. Francaise de la Lumière, 4 rue Ed.-Rousse, Paris 14e, France*

June

4–8 French Soc. of Physical Chemistry, Paris *Secrétaire Général, Société de Chimie Physique, 10 rue Vauquelin, Paris 5e, France*

5–8 24ème Congrès Annual du GAMS *Secretariat, 1 rue G. Boissier, Paris XV, France*

7–10 Canadian Association of Physicists 17th Annual Congress, Hamilton, Ontario,

11–14 Instrument Society of America, Seattle, Wash., Instrument-Automation Conference and Exhibit *W. H. Kushnick, 313 6th Ave., Pittsburgh 22, Pa.*

11–15 Columbus Symposium on Molecular Structure and Spectroscopy *R. A. Oetjen, Dept. Physics, Ohio State University, Columbus 10, Ohio*

18–22 Eindhoven Congress on Magnetic and Electric Resonance and Relaxation *D. J. Kroon, Natuurkundig Laboratorium, N.V. Philips' Gloelampenfabriek, Eindhoven, Netherlands*

18–22 International Conference on Spectroscopy, Univ. of Maryland *B. F. Scribner, National Bureau of Standards, Washington 25, D.C.*

19–21 APS Summer East Mtg., Evanston, Ill. *K. K. Darrow, Columbia Univ., New York 27, N.Y.*

24–29 ASTM National Meeting and Apparatus Exhibit, Statler Hotel, New York *ASTM, 1916 Race St., Philadelphia 3, Pa.*

25–29 Institute of Nuclear Magnetic Resonance, Buffalo *H. A. Symanski, Chemistry, Canisius College, Buffalo 8, N.Y.*

25–30 Copenhagen Symposium on Electromagnetic Theory and Antennas *H. Lottrup Knudsen, Oster Voldgade 10 G, Copenhagen K, Denmark*

July

— Munich Symposium on Crystallographic Computing *D. W. Smits, International Union of Crystallography, c/o Mathematisch Institut., Univ. of Groningen, Reitdiepskade 4, Groningen, Netherlands*

8–14 6th International Commission on Glass, Washington, D.C. *C. H. Hahner, General National Committee, c/o Glass Section, National Bureau of Standards, Washington D.C.*

9–11 11th International Astrophysics Symposium, Liège *P. Swings, Inst. of Astrophysics, Sciessin, Belgium*

9–20 Summer Course in Optics *Inst. of Optics, River Campus Station, Rochester 20, N.Y.*

10–20 Summer Course on Techniques of Infrared Spectroscopy *Director, Center for Continuation Study, Univ. of Minn., Minneapolis 14, Minn.*

16–19 International Colloquium on Novae, Novoids and Supernovae, Lyons *J. Dufay, U. de Lyons, rue de Cavenne, Lyons, France*

16–20 IUPAP Conference on Paramagnetic Resonance, Jerusalem *W. Low, Hebrew Univ., Jerusalem, Israel*

16–20 International Conference on the Physics of Semiconductors, Exeter. *IPPS, 47 Belgrave Square, London, S.W.1, England*

25–31 Symposium in Commemoration of Fiftieth Anniversary of the Discovery of X-Ray Diffraction and of Crystal-structure Analysis, Munich *F. Bopp, Inst. für Theoretische Physik, Schellingstr. 4–8, Munich, Germany*

August

— 3rd International IUPAP Symposium on X-ray. Microscopy and X-ray Microanalysis, Stanford *H. M. Pattee, Dept. Physics, Stanford Univ., Stanford, Calif.*

5–11 2nd International Congress on Radiation Research, Harrogate *A. Howard, Mount Vernon Hospital, Northwood, Middlesex, England*

6–10 Society of Photographic and Instrumentation Engineers Meeting, Biltmore Hotel, New York.

6–17 MIT Infrared Summer Course *J. M. Austin 7-103, MIT, Cambridge 39, Mass.*

13–15 Interdisciplinary Conference on Electromagnetic Scattering, Potsdam, N.Y. *M. Kerker, Clarkson College of Technology, Potsdam, N.Y.*

14–16 Boulder International Conference on Precision Electromagnetic Measurements *G. Birnbaum, Hughes Research Lab., Malibu, Calif.*

14–18 Fisk Infrared Summer Course *Director, Fisk Infrared Institute, Fisk Univ., Nashville, Tenn.*

19–26 Sixth General Assembly of International Commission for Optics and Congress on Image Formation, Munich *H. Schober, Institut für Medizinische Optik, Arnulstr. 205, Munich, Germany*

21–24 International Symposium of Far Infrared Spectroscopy, Sheraton-Gibson Hotel, Cincinnati *F. F. Bentley, ASD, Wright Patterson AFB, Ohio*

21–28 Copenhagen International Congress on Acoustics *F. H. B. Interslav, Tekniske Hojskole, Ostervoldgade 10, Copenhagen, Denmark*

27–29 7th Symp. Ballistic Missile and Space Technology *Aerospace Corp., P.O. Box 95085, Los Angeles 45, Calif.*

27–29 APS Summer West Mtg., Seattle, Wash. *H. A. Shugart, Physics, Univ. of Calif., Berkeley 4, Calif.*

27–30 American Astronomical Society Meeting, Yale Univ. *H. Smith, Yale U. Observatory, New Haven, Conn.*

27–31 Infrared Gordon Conference, Meriden, N.H.

27–Sept. 1 2nd International Conference on Information Processing, Munich *IFIPS, 1634 Arch St., Philadelphia 3, Pa.*

30–Sept. 5 Symposium on Photo Interpretation, Delft *Commission VII Intl. Training Centre for Aerial Survey, Kanaalweg 3, Delft, Netherlands*

September

— British Assoc. Advancement Science Int'l Meeting, Manchester *G. Allen, Burlington House, London, W.1, England*

3–7 Brussels International Symposium on Information Theory *F. L. Stumpers, Philips Research Labs, Eindhoven, Netherlands*

5–7 Emittance and Reflection of Radiation from Various Materials and Space Applications *Univ. of Dayton*

7–12 Kyoto International Conference on Crystal Lattice Defects *R. R. Hasiguti, Univ. Tokyo, Bunkyo-ku, Tokyo, Japan*

9–14 Dallas Technical Conference of the Illuminating Engineering Society

10–15 IUPAC Tokyo International Symposium on Molecular Structure and Spectroscopy *Science Council of Japan, Ueno Park, Tokyo, Japan*

16–20 Electrochemical Society Meeting, Statler Hilton Hotel, Boston, Mass.

17–19 9th Ottawa Symposium on Applied Spectroscopy *B. Farrar, J. T. Donald & Co. Ltd., 1181 Guy St., Montreal 25, Que., Canada.*

17–22 6th Intl. Congress on High Speed Photography, Scheveningen *J. G. A. de Graaf, 14, Burgemeester de Monchyplein, The Hague, Netherlands*

24–28 Union of German Physical Societies, Stuttgart *H. Franke, Verband Deutscher Physik. Gesell., Gänseheide 15A, Stuttgart, Germany*

October

— Infrared Information Symposium Fall Meeting Eastern States

— URSI Montreal Meeting *M. G. George, Thayer School of Engineering, Dartmouth College, Hanover, N.H.*

— Varian Annual NMR-EPR Workshop *Varian Assoc., Hansen Way, Palo Alto, Calif.*

4–6 **Optical Society of America 47th Annual Meeting, Manger Hotel, Rochester** *Hilda Kingslake,* 56 *Westland Ave., Rochester, N.Y.*

5 **OSA Annual Business Meeting,** *Manger Hotel, Rochester, N.Y.*

15–19 Instrument Society of America 17th Annual Instrument-Automation Conference and Exhibit *W. H. Kushnick, 313 6th Ave., Pittsburgh 22, Pa.*

Use of a Hardy Recording Spectrophotometer as a Spectroradiometer

W. J. Brown

A simple modification is described which permits Hardy recording spectrophotometers to be used as recording spectroradiometers.

Introduction

The Hardy recording spectrophotometer can be modified readily for the measurement of spectral energy distributions over the visible spectral region, of either primary light sources or secondary sources such as fluorescent materials with specified conditions of illumination. The modification to be described has been made to a Hardy spectrophotometer of the original General Electric version,[1] but a similar modification should be possible with the current version.[2]

Modification Required

Figure 1 illustrates the Hardy spectrophotometer set up as a spectroradiometer which records as a function of wavelength the ratio of the spectral radiances of two light sources. The integrating sphere is removed, and light is directed through the polarization photometer and the double monochromator in the opposite direction to that usually employed. Magnesium oxide surfaces placed at the positions usually occupied by the reflection ports in the sphere are illuminated uniformly by the sources under comparison, and light reflected at about 45° is accepted by the photometer. The usual spectrophotometer light source and its associated lens are removed, and replaced by a right-angled prism and a lens which images the monochromator slit on the cathode of an R.C.A. type 6217 photomultiplier cell.

With test sources such as fluorescent lamps which have approximately uniform luminance over a sufficient area, it is permissible to omit the magnesium oxide surface in the test beam and to place the source itself directly in the beam. If the source is large it may then be necessary to separate the test and reference beams further by using a totally reflecting prism in one or both beams.

The usual amplifier is not used but is isolated by a switch inserted in its output lead to the servo system. The photomultiplier signal is applied to the input of the servo system after amplification by an external frequency-selective amplifier of 1 cps bandwidth, tuned to the signal frequency of 50 cps which is the mains frequency in Australia.

A simple extension of the theory of the polarization photometer[3] to include the present arrangement shows that the pen plots, as a function of wavelength, the ratio of the spectral radiances of the test and reference magnesium oxide surfaces. The relative spectral energy distribution of the test source at any set wavelength is given by the product, at that wavelength, of the chart reading and the relative spectral energy of

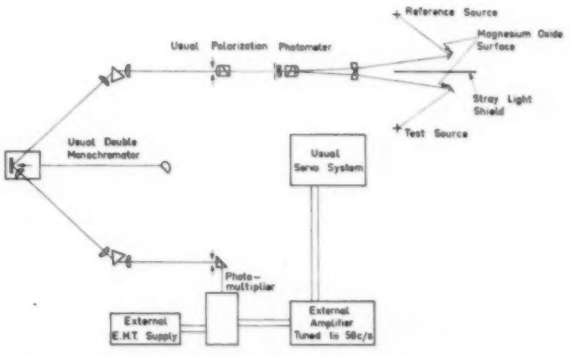

Fig. 1. Schematic diagram of a Hardy recording spectrophotometer modified for use as a spectroradiometer.

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the reference source. For most purposes, a C.I.E. Illuminant A source is a convenient reference. As usual with the Hardy spectrophotometer, corrections are necessary for differences in the spectral transmittances of the two beams; a "100% curve" can be obtained for this purpose by using identical sources in the two beams. To prevent the recorder pen running off scale when measuring line values and highly fluorescent samples, a calibrated neutral filter may be placed in the sample beam between the decentered lens and the magnesium oxide surface.

An important limitation to the spectroradiometer as described is that the photometer will balance incorrectly if the light emitted by the sources has components at the signal frequency (of the photometer) or at twice this frequency. This precludes measurements on most mains-operated lamps unless the signal frequency is altered, e.g., by operating the spectroradiometer from a power supply whose frequency differs from mains frequency. A change in signal frequency of about 10 cps enables the amplifier to reject unwanted signals adequately.

The possibility of obviating the frequency limitation by operating the test source on dc has been investigated for a number of fluorescent tubes, using a precision manually operated spectroradiometer. It has been found that the continuous spectrum components of the distributions of ac and dc operation at the same lamp power are not significantly different, but that the relative energies in the line components differ widely.

Only the horizontally polarized component of the test beam and the vertically polarized component of the reference beam are measured by the polarization photometer. This is a disadvantage with sources for which the degree of polarization varies with wavelength, but the same disadvantage is present to some extent in most spectroradiometers because of the variations in the transmittances of monochromators with the state of polarization of the incident light.

There are various well-known ways of overcoming such difficulties; as simple as any is to measure the two polarized components separately by turning the sample through 90°. The spectral energy distributions of the light in the two planes of polarization of a fluorescent lamp have been measured in this way and found to be identical.

Typical Results

Figures 2 and 3 illustrate results obtainable with the spectroradiometer. For these two sets of measurements, a right-angled totally reflecting prism was used in the reference beam, the reference source corresponded to C.I.E. Illuminant A, and the illumination of the reference magnesium oxide surface was about 19,400 lux.

Figure 2 was obtained with a sample of yellow fluorescent paint substituted for the magnesium oxide surface in the test beam, and with four different illuminants. The sample was illuminated approximately along its normal and viewed at 45° to the normal. The half-intensity bandwidth of the monochromator was 10 mμ, and each curve took 5 min to record.

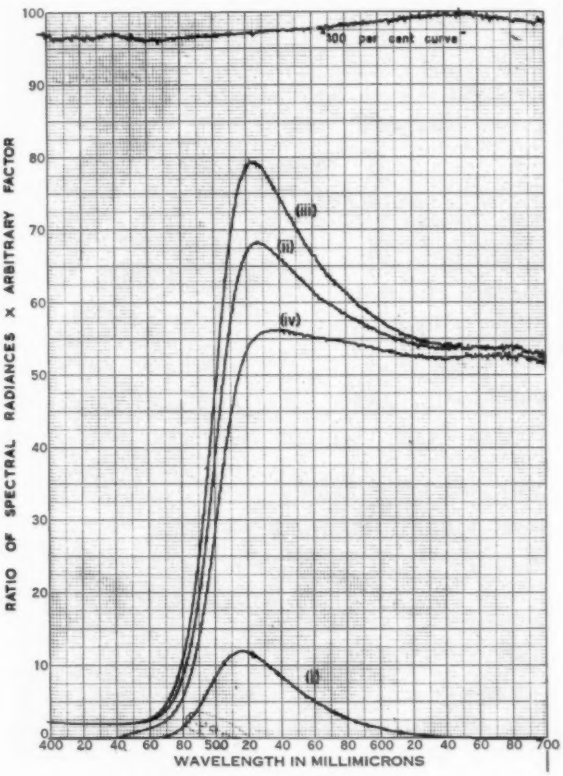

Fig. 2. The ratio of the spectral radiance of a yellow fluorescent paint to that of a C.I.E. Illuminant A source, plotted against wavelength over the visible spectral region. The four curves were obtained with the following sources illuminating the paint: (i) a mercury "black glass" lamp emitting radiation principally of wavelength 365 mμ; (ii) a C.I.E. Illuminant A source; (iii) sources (i) and (ii) together; and (iv) a C.I.E. Illuminant A source in conjunction with a sharp cutoff yellow filter of zero spectral transmittance at wavelengths less than 440 mμ.

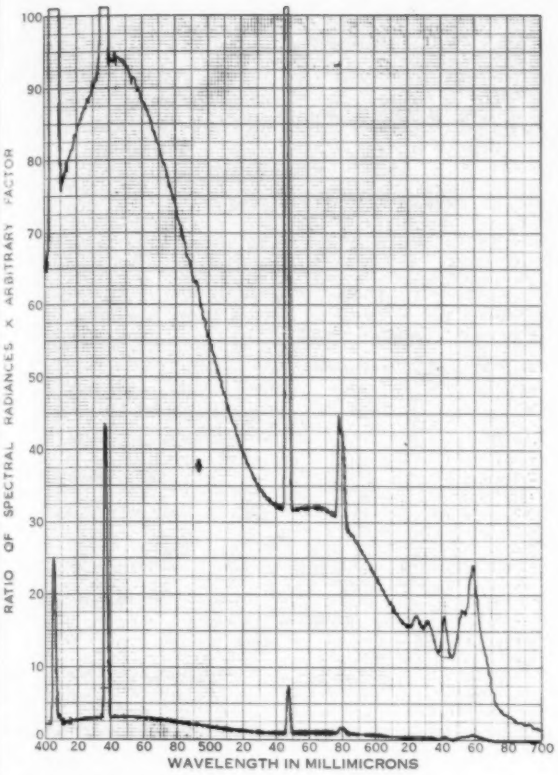

Fig. 3. The ratio of the spectral radiance of a dc operated "Daylight" fluorescent tube to that of a C.I.E. Illuminant A source, plotted against wavelength over the visible spectral region. The lower curve was obtained with a neutral glass filter in front of the fluorescent tube.

Figure 3 was obtained using a dc operated "Daylight" fluorescent tube as a direct source in the test beam, the measurements being made on light emitted approximately normally by a central area of the wall of diameter about 2 cm. The lower curve was taken with a neutral glass filter in the reference beam so as to indicate the relative strengths of the lines. The bandwidth of the monochromator was reduced to 2 mμ for these measurements, in order to resolve the fine structure in the red region. The curves were recorded at the same speed as those in Fig. 2 except in the neighborhood of the mercury lines where the wavelength was advanced slowly by hand.

Conclusion

The modification described provides a recording spectroradiometer which is suitable for a wide range of measurements. It should be particularly useful for control problems in the manufacture of fluorescent materials. The chief limitation is that the spectral energy distributions of most mains-operated light sources cannot be measured unless the signal frequency of the photometer is altered.

The author wishes to thank W. R. Blevin for his advice during this project.

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2. B. Pritchard and W. A. Holmwood, J. Opt. Soc. Am. **45**, 690 (1955).
3. A. C. Hardy, J. Opt. Soc. Am. **25**, 305 (1935).

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Reviews of some of these titles will appear in subsequent issues

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Wave Mechanics of Crystalline Solids, by R. A. Smith. Wiley, New York, 1961.

Optics in Great Britain

W. D. Wright, L. A. Sayce, and K. W. Greenland

The paper gives a general survey of the main institutions where research in optics is carried on in Great Britain. A more detailed account is given of the activities of the Light Division, National Physical Laboratory, the Optics Department, British Scientific Instrument Research Association, and the Technical Optics Section, Imperial College of Science and Technology.

Introduction

Optical research in Great Britain is being carried out in the universities, in government laboratories, and in industry. The inclusion of optics in the research program of a university department depends largely on the interests of the head of the department and of other members of the academic staff, since it is very much in the tradition of British universities that a wide measure of freedom should be allowed to the staff to choose their own special fields of study. Certainly there is no need to have a department labeled "Optics" before optical research can be undertaken.

As evidence of this we may quote the work of S. Tolansky on multiple-beam interference at the Royal Holloway College, London; the investigation of eye movements and the stabilized retinal image under R. W. Ditchburn at Reading University; the development of the reflection microscope by C. R. Burch at Bristol University; the study of optical imagery by E. H. Linfoot at Cambridge University; the development of photogrammetric equipment by E. H. Thompson at University College, London; the very active school of astronomical optics under Z. Kopal and J. Ring at Manchester University; the development of microscope techniques by R. Barer at Oxford University; varied aspects of physical optics being studied under A. M. Taylor at Southampton University; the design and construction of optical equipment for space research by R. L. F. Boyd at University College, London. In all this there is a refreshing variety of approach and much originality of thought, and the sum total represents a massive contribution to the science of optics.

The development and application of optical instruments and techniques also figure prominently in the work of several government institutions. For example, the Royal Aircraft Establishment at Farnborough naturally has a lively interest in aerial photography, the Atomic Energy Establishment at Harwell is involved in high-speed photography, and the Meteorological Office has developed spectroscopic equipment for ozone determinations in the upper atmosphere. In addition, several of the Research Associations operating under the Department of Scientific and Industrial Research, such as the Paint Research Station at Teddington and the Printing and Allied Trades Research Association at Leatherhead, have made very important contributions in photometry and colorimetry.

In industry, firms such as Kodak Ltd. and Ilford Ltd. have large research laboratories engaged in photographic research, much of which is optical in character. The firm of Pilkington Bros. Ltd. have recently opened a new laboratory devoted to research on the production and properties of glass, including optical glass. Other industries, such as the lighting industry, television, paint, etc., are also concerned to some extent with optical problems, and organizations such as Imperial Chemical Industries Ltd. and the Distillers Co. Ltd. are responsible for the development of optical techniques, and, indeed, of new optical equipment related to their own needs.

Of the lens and optical instrument manufacturers themselves, the new research laboratories of Hilger & Watts Ltd. in Camden Town are symptomatic of the recognition by the optical industry of the importance

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of research to the industry. The British optical industry, however, includes a considerable number of relatively small units and many of these are unable to maintain research departments of their own. Instead, as described below by Dr. Greenland, the services of the British Scientific Instrument Research Association are available to them.

This leads, then, to the work of the three institutions described in the following sections of this paper, namely, the Light Division of the National Physical Laboratory, the Optics Department of the British Scientific Instrument Research Association, and the Technical Optics Section of the Imperial College. We have here three departments which exist for the specific purpose of undertaking optical work; they have therefore been selected for a description of their work in greater detail. From what has been said above, however, it will be clear that much important optical work is in progress elsewhere.

The Light Division, National Physical Laboratory

The National Physical Laboratory at Teddington, near London, is the senior research establishment of the government-sponsored Department of Scientific and Industrial Research. The Light Division, with its staff of seventy persons, is the largest single unit in Britain devoted to research in optical and related problems. It is concerned with the practice of "optics" and with the study of radiation in the ultraviolet, visible, and infrared regions of the spectrum. Its radiation measurements are of two kinds; those within the visual spectrum using special units made to suit the eye—these comprise photometry and colorimetry—and those made over the whole range with physical receivers using the normal physical units of energy. The practice of optics provides the framework for this work and it has, in addition, its own field of study in interferometry, polarimetry, refractometry, and goni-

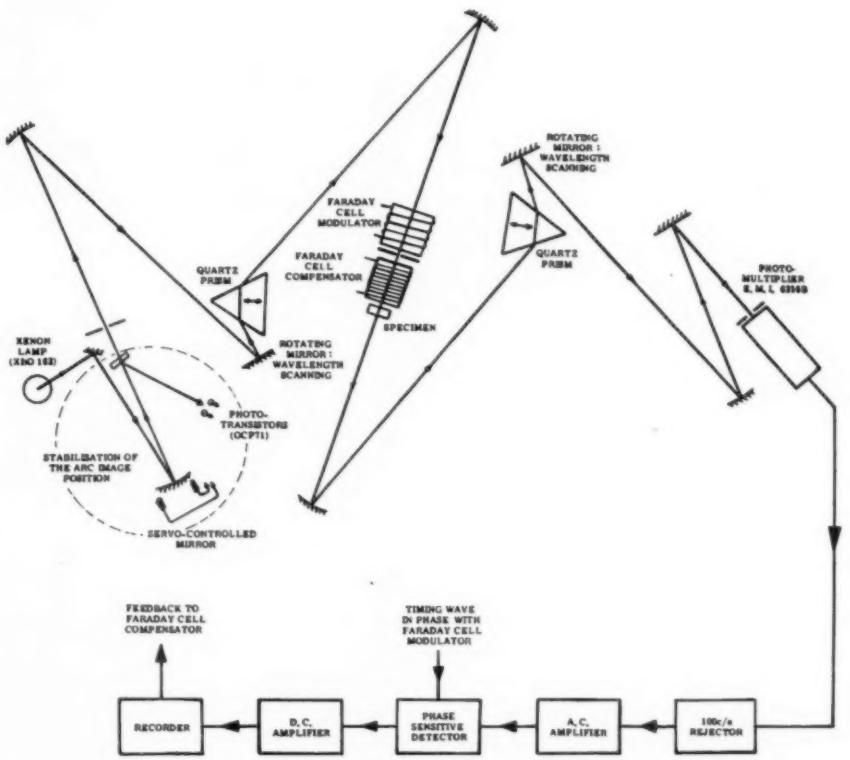

Fig. 1. N.P.L. spectropolarimeter. In this spectropolarimeter, two crystalline quartz prisms, cut with the optic axis at right angles to the prism base, are used both to disperse the radiation and to polarize it. The optical system closely resembles a double monochromator, wavelength scanning being provided by the rotation of two plane mirrors about a common axis. The optical rotation of the specimen is recorded in terms of current; this is derived automatically from an electronic system utilizing two Faraday cells with cores of fused silica. The wavelength range of the instrument is 200 mμ to 600 mμ, and the output noise level is less than 0.001° over most of this spectral range.

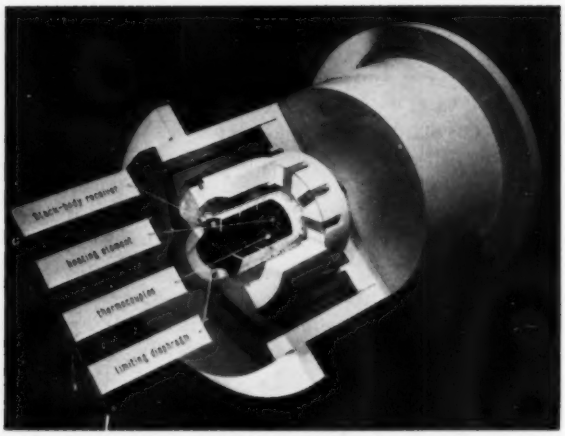

Fig. 2. Cut-away model of absolute radiometer developed in the Light Division, N.P.L., for fundamental measurement of radiant power. The radiation is totally absorbed in a blackbody receiver. The heat so produced is measured by comparison with heat produced electrically in an in-built resistive element.

ometry, together with an active interest in instrument design, "optical films," and lens computation.

The Division thus falls naturally into three main sections: General Optics, Radiometry and Standards, Photometry and Colorimetry. Each section has its own contributions to make to the maintenance of the national standards, its advisory and test services to industry, and its special researches. In addition there are Research Groups devoted respectively to optical masers and to diffraction gratings and their applications to industrial measurement and control problems.

The Division has two well-equipped workshops to meet the varied requirements, both optical and mechanical, of research apparatus and prototype instruments.

The *General Optics* Section is responsible for the study and design of lens systems and optical instruments of all kinds. It is equipped for the precise measurement of the properties of optical materials and components (refractive index, dispersion, curvature, transparency, reflectivity, etc.), and it advises upon lenses, telescopes, binoculars, theodolites, polarimeters, and other instruments submitted by instrument making firms. Research within this Section has produced many new optical instruments of which recent examples are an interferometer for the accurate assessment of spherical surfaces, a recording refractometer covering the range of 0.2 to 5.5 μ, and a photoelectric spectropolarimeter (Fig. 1) of high sensitivity with which the Verdet constants of various materials are being investigated. Within this section a research group has recently been formed to study optical masers and their application.

The *Radiometry and Standards* Section is primarily concerned with the nonvisual aspects of radiation but is also responsible for maintaining the standards of photometry. In the field of radiometry, experiments with a calibrated thermopile-filter combination, used as an "absolute physical eye," have shown the possibility of establishing such a device as the international fundamental basis of light measurement, instead of a material primary standard.

Successful development of new absolute radiometers (Fig. 2) has helped this work and now makes possible a more accurate measurement of the Stefan-Boltzmann constant and of temperature by total radiation methods. Complementary to this is the completion of apparatus for measuring absolute spectral energy distributions which it is hoped will also help in defining a source for supplying radiation of approximately solar intensity and quality. Work is also being done on the measurement of spectral absorption curves of actual radiation thermopiles.

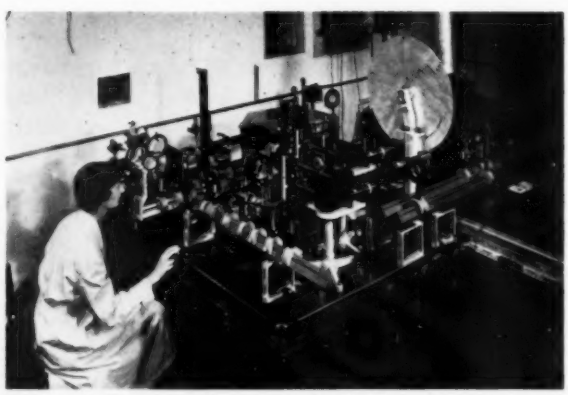

Fig. 3. Increment–decrement threshold equipment, in the Light Division, N.P.L., for studying the properties of the underlying receptor mechanisms of human vision. Screening has been removed. The equipment has so far been used for studying the form of the spectral response functions of the eye, their summation properties with respect to wavelength, luminance, and time, and the effect of various sources of scattered light in the eye on visual performance.

In the photometric standards laboratory, recently completely re-equipped with modern facilities and services, studies of the uses of automatic digital and new time-ratio methods in the measurement of light are in progress. A closer study of the properties of fluorescent lamps is proposed, as well as a wider study of fluorescence both as a phenomenon and a working tool.

The *Photometry and Colorimetry* Section is closely linked to the illumination industries; it supervises the routine photometric work of the Test House and undertakes the measurement of candlepower distribution and luminous flux from fittings and special light

sources of all kinds, the checking of photometric apparatus, especially illumination photometers, and the testing of luminescent materials.

The Section is also concerned with the selective absorption and emission of radiation which, in the visible region of the spectrum, results in color. Measurements are made by spectrophotometers and colorimeters, several of which have been developed in the Section and have now become standard instruments in industry. Color measurements are made in terms of the colorimetric system adopted in 1931 by the International Commission on Illumination. Such measurements are the basis of many British Standards used by the color industries and the transport authorities. Of special importance are the color standards for road and railway signals, navigation lights (sea and air), and airport markers.

Visual research is in progress to provide more precise definitions of the brightness-matching and color-matching properties of the average human eye and a better understanding of the mechanisms of color vision (Fig. 3). A study of color rendering has led to a simple but informative method of assessing the color rendering properties of a light source. Work is in progress to increase by various methods the accuracy of photometric methods, especially in spectrophotometry, and to determine, absolutely and to a high accuracy, the spectral reflectance of diffusing surfaces. These two studies, in conjunction with the color-matching research, aim at bringing the accuracy of physical measurements into line with the high sensitivity of the eye to small color differences—an essential step in the replacement of material standards by absolute physical measurement.

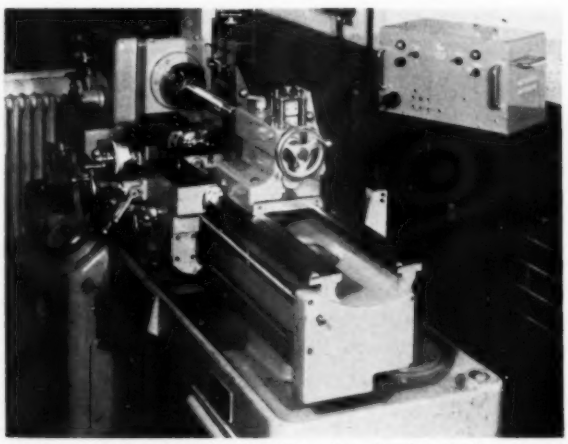

Fig. 4. Light Division, N.P.L., has developed the use of diffraction gratings for precise linear and angular measurement. In the tool room lathe shown above the linear movement of the tool saddle and the rotatory movement of the work-piece are monitored by suitable gratings and accurately related by a servo system.

The research on *diffraction gratings* which originally sought only to satisfy the requirements of spectroscopy has recently acquired a much wider significance. A study of the production of "moiré fringes" by crossed gratings has established their use in the precise measurement of lengths and angles, and methods have been devised, using linear and radial gratings, for relating any two linear or circular movements and, if required, for correcting errors in the nominal relationship by application of a servo system. This research is thus laying the foundations for far-reaching developments both in rapid and precise measurement and also in the improvement of machines and machine tools (Fig. 4). To anticipate the consequent demands of industry, the Division is taking steps to ensure a supply of master gratings of various kinds, copies of which are being made generally available.

The study of *optical masers* is a recent addition to the work of the Division and at present effort is mainly directed to pulsed ruby masers at room temperature and samarium-doped calcium fluoride masers cooled by liquid helium. While it is hoped also to study resonator materials, the chief interest will be in the many applications to physical optics that are made possible by the high intensity and coherence of maser sources.

Optics at the British Scientific Instrument Research Association

The purposes of a British research association are to carry out basic research on subjects of special importance to the industry which it serves, to apply the results of research and of industrial developments to the improvement of the products of its own industry, and to assist its members collectively and individually in the solution of day-to-day and long-term problems of design and manufacture. Most research associations also run testing and information services.

The British Scientific Instrument Research Association is the oldest of the 47 research associations now in action. It was established in 1918 (with the help of the Department of Scientific and Industrial Research) at the request of a group of optical firms, and in its early years there was a strong bias towards optics in the research program. An interesting project at this stage was the design of photographic equipment for the Mount Palomar Observatory. Today the Association's laboratories at Chislehurst, near London, cover all aspects of instrumentation but optical research is still one of the major activities.

The design of optical systems has naturally run a steady course throughout the life of the Association. In this field the peculiar advantage of a research association to a complex industry is illustrated by the fact that the Optics Department is called upon to design infrared and visible range optical systems for instruments under development in the electronics,

Fig. 5. Two examples of the position-sensitive photocell ("Wallmark diode") as developed at B.S.I.R.A. for use in optical instruments.

nuclear power, or process control sections of the instrument industry.

Even within the optical industry itself, as Professor Wright has pointed out, some firms are too small to be able to support an experienced optical designer and instead they rely upon the Association for all but the simplest lens computations. The Association has recently worked out a lens design program for the IBM 7090 computer, based on C. G. Wynne's "SLAMS" system for automatic optimization. In addition to providing a rapid computing service for members needing new lens designs, this facility is also the tool for an investigation into the possibility of rationalization of the range of glasses required for the design of high-performance lenses.

The assessment of lens performance in terms of the spatial frequency response function calls for apparatus of sophisticated design, of highly accurate construction, and of reproducible performance. As far as the generation of the test pattern and measurement of the response function are concerned, development is well under way at B.S.I.R.A. Provisional patent cover has been obtained for a system in which the variable frequency pattern is generated either by a cathode ray tube or by mechanical means; the amplitude and phase of the image are measured by a null method, comparison being made with the image formed by a reference lens.

The aim of this phase of the work on frequency response is to provide Government Services departments and lens manufacturers with standard equipment for measurement of the resolving power of lenses. Financial support for this project is now assured by a Ministry of Aviation contract.

Turning now from the optics of lens design and testing to the wider scope of optics in modern industry, we may remark that the interdependence of optics and electronics in instrumentation is nowadays so close that the expert in either subject must have more than a passing acquaintanceship with the other discipline. This is essential if the development of a new instrument is not to be shuttled between the two departments, to the detriment of progress and tempers. At B.S.I.R.A., the Optics and Electronics Departments share the same laboratory block; the senior optical scientist, L. R. Baker, spent three years designing electrical servo systems.

A typical example of the Research Association method is afforded by the history of a recording autocollimator recently produced by B.S.I.R.A. A highly sensitive position-sensing photocell was described in 1957 by J. T. Wallmark of R. C. A. This was noted by the Optics Department. When the opportunity to expand the Association's research program occurred, the development and assessment of this cell was put in hand, and in a comparatively short time the technique of constructing a "potted" cell suitable for industrial conditions was worked out (Fig. 5). The characteristics of the cell were charted and circulated to members together with a survey of possible applications. One of the Association's members, Hilger & Watts Ltd., then took over the manufacture of the cell, and another member, W. Ottway & Co. Ltd., commissioned the

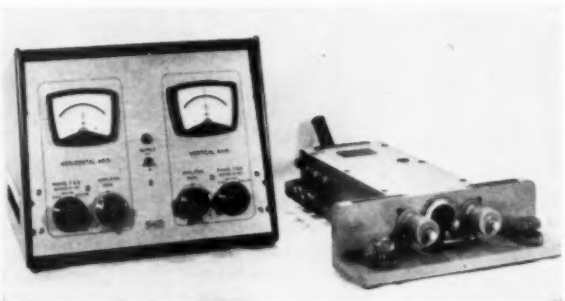

Fig. 6(a). The experimental prototype of an electrical autocollimator utilizing the position-sensitive photocell.

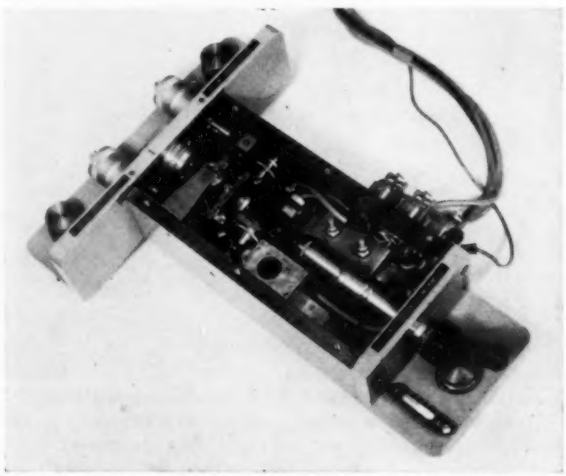

Fig. 6(b). The collimator with cover removed. (by courtesy of W. Ottway & Co. Ltd)

Fig. 7. Taking a sample from the melt of a new glass in the B.S.I.R.A. furnace room.

Association to design a laboratory prototype autocollimator using the Wallmark cell for measuring and recording small angular deviations [Figs. 6 (a) and (b)]. The design of this instrument demanded the closest possible integration of optical and electronic design to achieve a stability of one second of arc over periods of many hours.

In the case of the electric autocollimator the type of construction was only that required to demonstrate the ability of such an instrument to meet the specification for performance; design for production was in this case handled by the sponsor. In other cases of sponsored development, the instrument may have to be constructed to meet a performance specification under normal industrial conditions, and a production prototype will be designed and made. For instance, a total-radiation pyrometer for measuring surface temperatures down to 50°C and capable of withstanding jolts of $10g$ acceleration is now undergoing field trials after the optical principle had been proved on a laboratory model. The special feature of this instrument is that the indicated temperature is independent of the emissivity of the surface under measurement, at least within the emissivity range 0.2 to 0.9. This project was also commissioned by a member, the British Transport Commission. Sponsored research of this type provides a supplementary source of revenue but is not allowed to exceed an agreed proportion of the total research effort.

Many special optical instruments for the monitoring and control of chemical and metallurgical processes are developed by the companies engaged in these industries. For instance, some very effective instruments based on characteristic infrared absorption have come into use on chemical plant, and there is an increasing demand for low-temperature radiation pyrometry in the production of plastics and metals. The infrared detector is, of course, the common factor in all these instruments, and the Association's Optics Department therefore takes a special interest in the characteristics and applications of all types of infrared detector. A total-radiation furnace operating at 200°C and provided with a temperature-controlled chopper and variable aperture at 20°C has been set up; with the cooperation of the National Physical Laboratory this apparatus has been proved to be a true blackbody radiator at 200°C. Any radiation detector can be aligned with the radiator in a temperature-controlled chamber and its responsivity and noise equivalent power measured. In connection with the use of infrared detectors, some preliminary work has been carried out on the design of refracting optics for the infrared region; an achromatic doublet has been designed for the region 2–7μ.

The research projects and major sponsored items so far described account for about two-thirds of the current output of the Optics Department. The remainder of the Department's effort is absorbed in services to individual members: these services include routine measurements such as lamp and photocell calibrations, checking of parameters on the optical bench and with interferometers, optical transmission measurements and, generally, assistance in day-to-day problems where optical methods are useful. Finally, instruments under development or in use by members' firms may be submitted to B.S.I.R.A. for an analysis of their performance, especially when the instrument is not performing satisfactorily; the laboratory usually has a free hand to redesign the optics and the electronics to improve performance. Here again the disastrous effect of imperfect coordination of these two functions in the original design is sometimes encountered.

The present time is a period of transition for many of the smaller British optical firms, in that these firms are turning to industrial instrumentation for wider markets. In this realm electrical outputs are essential for recording and for feedback to control points, but the habit of thinking in terms of both optics and electronics simultaneously takes time to acquire. It is for this reason that the Optics Department of the B.S.I.R.A., closely supported by the Electronics Department, is so much concerned at present with the design of prototypes. Nevertheless, our first duty is to continue the search for new optical methods and for applications of new devices.

The formulation of special glasses has always been one of the main interests of the Chemistry Department (Fig. 7). This activity has recently been widened by a joint investigation with the Nucleonics Department into the preparation and applications of glass scintillators: these are for the detection of α, β, and γ radiations and thermal neutrons. The durability of a glass scintillator and the fact that it may be produced in a variety of geometrical forms by the normal glass-

making technique make it an attractive proposition in nucleonic instrumentation.

The mechanism of glass polishing is also a major subject of research in the Chemistry, Mechanical Engineering, and Electron Microscopy Departments. The first objective is a thorough investigation of the effects on polishing rate of all the controllable parameters (such as the density, temperature, and pH value of the slurry, and the pressure of the polisher). This collection of data will then provide a basis on which theories of the mechanism of polishing can be tested. The ultimate aim is the practical one of improving the efficiency of the polishing process.

It is apparent that the interest in research and development shown by manufacturers and users of optical instruments indicates a lively appreciation of the future of optics in industry.

The Technical Optics Section, Imperial College

Specialized instruction in optics has been given at the Imperial College since the Department of Optical Engineering was established in 1917. In 1931, however, the status of the Department was changed to that of a Postgraduate Section of the Physics Department, and students attending a one or two year course of advanced study can sit for the Diploma of Membership of the Imperial College and the London University M.Sc. degree in Technical Optics.

There is an academic staff of 8 who are responsible for the instruction and research supervision of some 25 postgraduate students and research assistants. In addition, certain members of the staff have wider responsibilities in the Physics Department and with the optical instruction of physics undergraduates.

The original purpose for which the Department was created was to increase the number of people trained in lens design and in the use and testing of optical instruments. A. E. Conrady developed the original courses on optical design, and instruction in this subject has remained one of the most important functions of the Section. Recently, the Department of Scientific and Industrial Design awarded a long-term grant for the establishment within the Section of an Optical Design Group under C. G. Wynne. This Group will be particularly concerned with the development of new techniques in optical design using electronic computers.

Research in various branches of optics has come to play an increasingly important part in the work of the Section. Thus B. K. Johnson has studied a variety of problems in microscopy, particularly in ultraviolet microscopy and microspectrophotometry. Objectives have been designed for the short-wave ultraviolet region, and also supplementary optical systems for insertion between a quartz monochromat and eyepiece for simultaneous focusing with visible and ultraviolet radiations. One of his most novel instruments has been a microscope system operating in nitrogen for use in the short-wave region where air begins to absorb.

A number of researches are in progress under the direction of H. H. Hopkins. He himself, of course, has carried out important theoretical studies on aberration theory, problems of partial coherence, aberration tolerances, Fourier methods for analyzing the performance of optical systems, and the numerical evaluation of the frequency response of a system. Experimental work in this field, supported with a contract from the Ministry of Aviation, includes the measurement of the frequency response function by a scanning instrument and by an interferometer. The spatial frequency spectra of photographic transparencies are also being studied.

In the first scanning method to be used the enlarged image of a fine slit is scanned in order to measure the spread function, that is, the distribution of intensity in the image of a slit. From this measured spread function the frequency response may then be calculated numerically. The scanning slit is then replaced by a variable-velocity scanning drum. This drum has a series of fine slits spaced about 12 mm apart around its periphery and the drum is rotated at high speed, each slit scanning the spread function in turn. The total light flux passing through the rotating drum is detected with a photomultiplier and tuned amplifier. It can be shown that for certain definite speeds of rotation the ac output of the detector is a measure of the frequency response for a definite spatial frequency. Hence, varying the speed of rotation and measuring the output at these resonance points gives a series of equally spaced points on the frequency response curve. This method has been used to verify a large number of cases of frequency response curves for defocused images.

A modification of this method has been proposed and used in which the scanning drum has a 50 lines per cm, black and white, grating around its periphery. The spread function is limited in height by means of a slit and then re-imaged onto the drum which now rotates slowly at a constant speed of about 1 rev/sec. The spread function formed on the drum is rotated from a position where it is parallel with the lines of the grating to a position where it is perpendicular to the lines. In so doing the output from a photomultiplier receiving the light transmitted by the scanning drum has an ac component which is measured, and this gives the frequency response continuously as a function of frequency. This method has advantages over the variable-velocity drum, in that the response curve can be directly normalized for zero frequency, the curve traced by the pen recorder is a continuously slowly varying curve, and all that the drive of the scanning drum requires is a synchronous motor and reduction gear.

This second scanning method still presents difficulty if one wishes to measure the phase of the frequency

response. A proposal has been made, and is at present being instrumented, in which a similar technique can be used to measure the real and imaginary parts of the frequency response separately. When this work is complete one can be confident that a good solution will have been reached of the practical problem of measuring the whole frequency response characteristic of lenses reliably and with comparatively simple apparatus.

The principle of a new interferometer which is self-compensating and which has been developed to measure the frequency response function is illustrated in Fig. 8.

Frequency response studies of the photographic process have been carried out using a modified Michelson interferometer to produce two-beam interference fringes to form a sinusoidal test object. The spacing of the fringes can be varied at will, and for any given spacing the fringes can be caused to move laterally in a direction perpendicular to their length. If these fringes fall on a photographic transparency and the total light flux transmitted is measured as the fringes are displaced laterally, this light flux contains a constant and a varying component. The amplitude of variation is a measure of the amplitude of the Fourier spectrum of the distribution of opacity over the plate, and hence the instrument constitutes an optical Fourier analyzer. There remains the important question, namely, whether the sensitivity of frequency response as a means of assessing image quality is greater than the sensitivity of assessment of image quality made subjectively by observers. An experimental study of this question is now in progress.

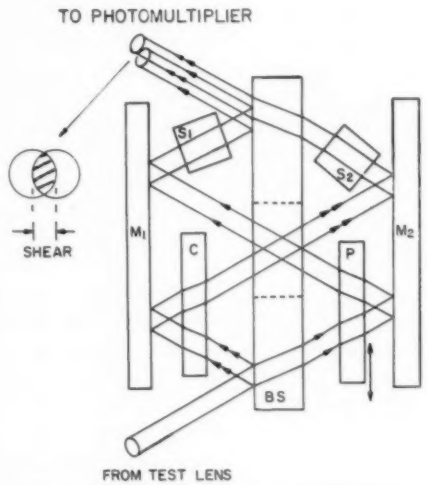

Fig. 8. An interferometer for the measurement of optical frequency response. Light from an entrance slit is collimated by the test lens and is incident on the interferometer assembly as shown. A shear is introduced between the two beams leaving the interferometer by means of the shear plates S_1 and S_2. Fringes are then formed between the overlapping portions of the two sheared beams, any given shear corresponding to a definite spatial frequency. The light flux in the overlapping portion is caused to vary sinusoidally by the reciprocating movement (which has a linear velocity in each direction) of a small-angle prism P in one arm of the interferometer. The ac component of the electrical signal produced when the total light flux is incident on a photomultiplier is fed, after amplification, to an ac pen recorder. The amplitude of the ac signal relative to that in the nonsheared pupils gives a modulus of the frequency response function for the particular value of the spatial frequency. Continuous variation of the shear by rotation of S_1 and S_2 enables the frequency response curve to be recorded. A point to be noted is that because each beam is reflected from the beam splitter BS and the mirrors M_1 and M_2 there is automatic compensation for tilt between the two emerging beams.

Work on fiber optics also in progress under the aegis of Dr. Hopkins is largely directed towards the development of practical methods of making high-resolution systems. It is felt that systems using multiple-cored fibers of about 0.005-mm core diameter are particularly worthy of attention. Multiples are produced by a double drawing method which is still being evolved. The original stock is of the type where a rod to form the core and a concentric tube of sheathing glass are drawn down together. Any diameter from 0.5 mm to 0.01 mm or less can be produced with the equipment available.

The production of high-quality flexible assemblies still produces some difficult problems. Finishing of the ends is currently performed by embedding in polyester resin and polishing by a slight variant of traditional glass-working techniques. The winding of single-layer sheets is being investigated as a step towards a better understanding of the dynamics of multiple-layer winding. An interesting sideline, as yet of no optical use, has been the production of sheets of aligned acrylic microtubing.

A novel by-product at one stage was helically coiled fiber, such as might be used in delicate spring suspensions, in continuous lengths. This was made by chilling the fiber on a small-diameter pulley immediately below the drawing point where it is still soft. If the radius produced is not too small the fiber can be drawn straight down from this point onto a large drum for storage.

Recent work in the department on absorption measurements in slabs of optical glass has produced some valuable data for fiber optics, but further measurements are needed, particularly for the comparison of fiber and bulk transmissions of the more transparent glasses.

W. T. Welford is in charge of other research projects, one of the most dramatic being connected with the British National Hydrogen Bubble Chamber Project. The main part of this project is centered at the Rutherford Laboratory, National Institute for Research in Nuclear Science, Harwell, but the work in this department is concerned with the design and construction of optical systems for large (ca. 500 liter) bubble chambers using liquid hydrogen and liquid helium. Tracks of

ionizing particles appear as curved lines of bubbles about 0.1 mm in diameter and these must be photographed throughout a volume approximately 150 cm by 50 cm by 40 cm deep in the case of hydrogen with an exposure not exceeding 200 μsec. The refractive index differences between liquid and vapor are very small, 0.1 for hydrogen and 0.025 for helium, and the tracks must therefore be photographed in dark-ground illumination with a small angle (a few degrees) between direct and scattered light. In order to evaluate the photographs, film measuring machines are being designed and constructed which will set on a track and follow along it automatically, punching coordinates on computer tape at chosen points; the coordinates are measured by moiré fringe digitizers with 1 μ digits and an overall accuracy of ± 2 μ is aimed at. This corresponds to determining spatial coordinates in the chamber with an accuracy of ± 30 μ transverse to the direction of photography and, by stereo reconstruction from three views, about ± 100 μ in depth.

Another project under Dr. Welford is that being undertaken for the National Coal Board on the counting and sizing of dust particles. A recent aspect of this work is concerned with the production of nonperiodic test objects of known size and shape in the submicron size range and the determination of the light distributions in their images when formed by microscope objectives of high numerical aperture. The relations between these light distributions and the visual images as modified by Mach effects is also being investigated.

Color has for many years provided a field of research for another group in the Section and has been concerned on the one hand with the technical aspects of colorimetry and spectrophotometry and their applications to industry, and on the other with the visual processes and the characteristics of normal and defective color vision. A recent project in the technical field has been an attack on the problem of high-accuracy colorimetry and spectrophotometry. It is generally agreed that at least in certain industries the accuracy to which colors can be measured needs to be improved, and one way of meeting this demand is to prepare an extensive series of reference standards that have been calibrated to the highest possible accuracy. Industrial standards can then be measured relative to these reference standards by means of differential spectrophotometry and colorimetry.

Initially a series of grey ceramic tiles ranging from black to white, with quite small intervals of luminance factor between one tile and the next in the series, are being calibrated spectrophotometrically. Check measurements are being obtained by differential reflection measurements between neighboring tiles in the series and by other photometric and colorimetric measurements. These tiles will then be available for the calibration of colored standards by differential spectrophotometry and colorimetry. As part of the project, a new differential spectrophotometer, a new visual differential colorimeter, and other equipment are being developed.

On the biological side a survey is in progress to study the relation between color vision and age. Some 500 subjects between the ages of 15 and 70 are being examined with a variety of tests including color matching on a trichromatic colorimeter, measurements of V_λ and wavelength discrimination at selected wavelengths in the spectrum, examination with the Farnsworth-Munsell 100-Hue test, and with the Ishihara and similar charts. Another investigation is concerned with methods of subjective color measurement and their use in the study of color contrast effects.

There is thus considerable variety in the research activities of the Section as a whole. Clearly not every branch of optics can be represented and the choice is determined by the interests and special knowledge of the staff, by the availability of funds to support particular projects, and by the value of the research as a training ground in optics for postgraduate physicists and other students.

G. D. Robinson *Bracknell, England* and F. Möller *Munich* during the Vienna WMO meeting last August

A Method for Obtaining Accurate Half-Intensity Widths of Spectral Lines Photographed in the Vacuum Ultraviolet

B. B. Jones

A method has been developed for finding the half-intensity width, to an accuracy of ±5%, of the profiles of spectral lines photographed in the vacuum ultraviolet. Plate calibration is achieved by an aperture restriction device placed at the Sirks focus of a 3-meter normal incidence vacuum spectrograph. This gives a stepped intensity in the focal plane with a standard ratio of 2:1. The measurement is not affected by reciprocity law failure or intermittency effect in the photographic emulsion, and can be used with pulsed light sources.

Introduction

Measurements of the Doppler broadening of spectral lines emitted by highly ionized impurity atoms have been used to estimate ion energies achieved in the experimental gas discharge apparatus Zeta.[1] Previous measurements[2] have been restricted to the visible and quartz ultraviolet regions of the spectrum. The extension of photographic work to the vacuum ultraviolet is dependent on some method of calibrating the photographic emulsion in this region. Since highly ionized atoms emit strongly in the vacuum region, accurate measurements at these wavelengths have become a necessity, and recent investigations into the ion heating mechanism in Zeta[3] have been carried out in this part of the spectrum using the calibration method described here.

For the purposes of this work the average kinetic energy of an ion is estimated by measuring the half-intensity width of the line. The observed profile is usually in the form of a transmittance or density curve, and knowledge of the relation between photographic density and light intensity is needed to convert to an intensity distribution. The method of a stepped neutral filter frequently used in the visible and quartz regions cannot be applied to the vacuum ultraviolet because of the absence of suitable filters. Some methods investigated recently at this laboratory, using pulsed sources in the vacuum ultraviolet, are:

(a) A photoelectric measurement of the intensity ratio of spectral lines in the same multiplet. The measured intensities are then related to the photographic densities of the members of the multiplet to obtain a section of the gamma curve for that wavelength. The intensity ratios are measured since the theoretical values can be in error due to effects such as self-absorption.

(b) A photoelectric measurement of the variation of the intensity of one spectral line with different source excitations, the measurements being used as in (a).

(c) Variation of exposure time to alter the blackening on the photographic plate, and plotting density against the logarithm of the time to obtain a gamma curve over the range covered.

The first two methods can give accurate results, but are limited in range and cumbersome to use experimentally, and for a pulsed source require good reproducibility. The third method introduces errors due to reciprocity law failure, depending on the emulsion used. Experiments on Zeta, which is a pulsed discharge operating once every forty seconds, with a light pulse duration of approximately one millisecond, showed that method (c) gave errors of up to 50% in the intensity ratio of the O VI doublet at λ 1031 Å and λ 1037 Å, on Ilford Q.2 emulsion, when compared with a photoelectric measurement made at the same time.

Method

It is not necessary, in principle, to construct the complete characteristic curve of the photographic emulsion used in order to measure the line width. The determination of one point on the profile corresponding

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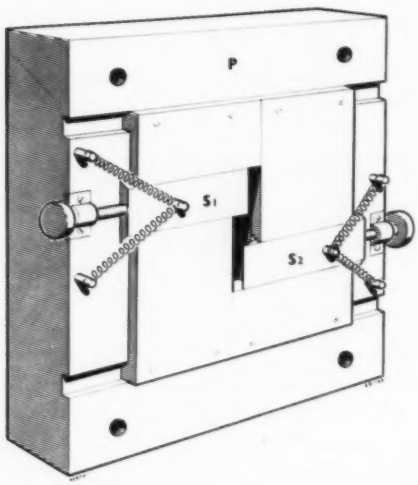

Fig. 1. Aperture restriction device placed before the entrance slit of the spectrograph to produce a stepped intensity distribution in the final image with a ratio of 2:1.

to the half-intensity height is sufficient. To achieve this, the beam entering a 3-meter normal incidence concave grating vacuum spectrograph, having a reciprocal linear dispersion of 2.8 A/mm, and an aperture of $f/30$, was divided into three equal sections along the length of the entrance slit by means of an aperture limiting device placed in front of the slit. The center section of the beam filled the aperture of the spectrograph and illuminated the whole of the grating. The outer sections were restricted in aperture to illuminate opposite halves of the grating respectively. The resulting slit image on the photographic plate was formed therefore by a bright central part with two fainter outer sections.

If I is the intensity in the central image, and I_1 and I_2 the outer intensities, then we have

$$I = I_1 + I_2.$$

If $D(I)$ is the density produced by intensity I, then the half-intensity point in the bright image is given by

$$D\left(\frac{I}{2}\right) = D\left(\frac{I_1 + I_2}{2}\right) = {}^1/_2[D(I_1) + D(I_2)] \text{ for } I_1 \simeq I_2.$$

Any small corrections due to $I_1 \neq I_2$ can easily be estimated using an approximate calibration. In the present work $I_1 \simeq 1.02\ I_2$, and the corrections were negligible.

If now the three parts of the image are microphotometered, the mean of the peak heights of the outer profiles corresponds to the half-intensity position on the center profile, and a measurement at this point yields the half-intensity width of the line. This procedure is valid for every spectral line photographed on the plate since the method employs a "built-in" standard intensity ratio of 2:1 which is independent of wavelength.

Figure 1 shows the method used to restrict the apertures of the outer sections of the beam. P is a brass plate, having a rectangular aperture 10 mm × 4 mm cut through its center, and was mounted in front of the spectrograph entrance slit, which was 9.0 mm long and 0.015 mm wide. S_1 and S_2 are slit blades moving in guides attached to the mounting plate, and were operated by micrometer threads working against tension springs. Initially the slit blades were withdrawn to leave the aperture open, and each blade was then moved in until it cut off one-half of its beam. The positioning of the aperture limiter in relation to the entrance slit was dictated by the need to overcome the astigmatism introduced by the concave grating and obtain sharp demarcation between the central and outer sections of the image, while retaining the image of the entrance slit to form the spectral line on the photographic plate. A limiter placed in the plane of the entrance slit would meet neither of these requirements, whereas with the plate P mounted so that the plane of the slit blades S_1 and S_2 coincided with the Sirks focus position of the spectrograph,[4,5] i.e., where horizontal lines must lie to be sharply imaged in the focal plane, both considerations would be satisfied. Figure 2 shows the position of the aperture limiter at the Sirks focus XX, which lies on the tangent to the Rowland circle at P, where NP is the grating normal. In the spectrograph used, XX lies approximately 9.0 mm in front of the entrance slit for the spectral range required. At an aperture of $f/30$ this gives an unrestricted entrance beam width of 0.30 mm at this point, for an infinitely narrow entrance slit.

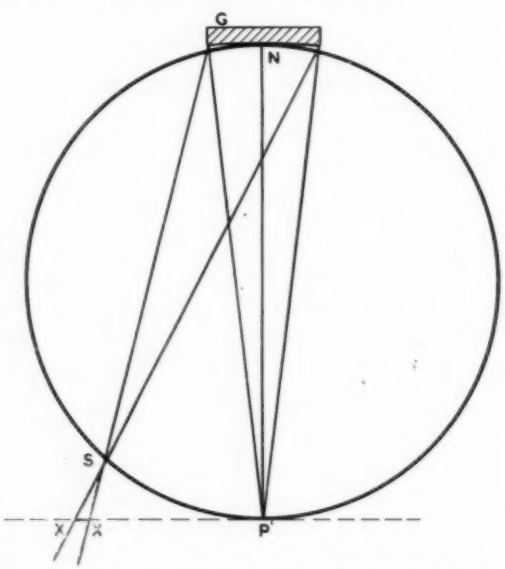

Fig. 2. Construction for the horizontal image position (XX) at the Sirks focus of a concave grating spectrograph. The aperture limiter is placed at XX on the tangent at P. S, entrance slit; G, concave grating; NP, grating normal; P, image on Rowland circle.

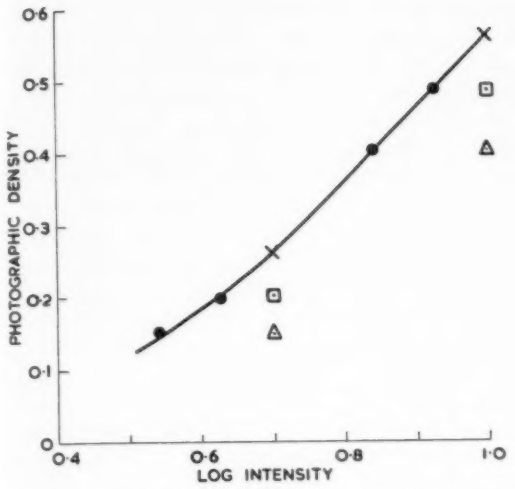

Fig. 3. A section of a characteristic curve for Ilford Q.2 emulsion, constructed using the aperture limiter and the O VI resonance doublet λ 1031 Å, λ 1037 Å, photographed in the Zeta spectrum. The composite curve was obtained by superimposing the parts given by exposures 2 and 3 on exposure 1. ×, exposure 1; □, exposure 2; △, exposure 3; ●, superimposed points.

Calibration

Preliminary adjustments were made visually, using the zero-order image, and observing the area of the grating illuminated through the exit slot of the spectrograph. Further corrections were made using a chopped light source, with a photomultiplier observing the zero order image in the focal plane, and the signals displayed and measured on an oscilloscope, tests having been made previously that the source gave a uniform intensity distribution along the unobstructed entrance slit. The slit blades were adjusted until the signals due to the intensities through the outer sections of the slit were approximately equal, and their sum was equal to the intensity signal through the unrestricted center aperture. The readings could only be made approximately equal due to the design of the slit blade movement. This allowed the blades to be moved in steps of 0.012 mm, the blades being locked in position after each step by a click-stop device not shown in Fig. 1. Small masks were used to blank off the light through the center and one outside section, while adjustments were being made to the other section. After the correct settings had been obtained, the photomultiplier was rotated through 180° about its longitudinal axis, and the ratios rechecked to avoid errors due to any non-uniformity in sensitivity over the cathode surface. The measurements showed a difference of less than 2% when comparing the mean of the outer intensities with half the center value.

Experimental Tests

The accuracy of the method was tested experimentally by using it to photograph the resonance doublets of O VI λ 1031 Å, λ 1037 Å; Ne VIII λ 770 Å, λ 780 Å, and A VIII λ 700 Å, λ 714 Å in the Zeta spectrum, and comparing the peak intensity ratios of the doublets measured photoelectrically with the ratios given by characteristic curves constructed using the aperture limiter. The device was used to obtain a part of the characteristic curve for the emulsion (Q.2) by means of three exposures, of the same duration, but with different source excitation to vary the intensity in small steps. The three sections of the image of the intense member of a doublet were microphotometered on each exposure and the densities calculated. The central density and the mean of the outer densities were then plotted against an arbitrary Log Intensity scale. The value of Log I_{max} for the central image on each exposure was taken as 1.00, and a ratio of 2:1 was assumed between the central intensity and the mean of the outer intensities. The pairs of points obtained from the three exposures were then superimposed to form a composite curve. The upper points of exposures 2 and 3 were assumed to be on the linear part of the characteristic, the slope of which was given by exposure 1, and the two lower points were adjusted a similar amount to their corresponding upper points. The curve for the O VI doublet is shown in Fig. 3. The central image of the weaker member of the doublet in each exposure was then microphotometered, its density calculated, and the intensity ratio found by using the composite curve. The values were then compared with a photoelectric measurement made at the same time. Similar curves were constructed for the Ne VIII and A VIII doublets, and the results for the three ratios are shown in Table I, together with the photoelectric measurements. In all three cases the photographic value of the ratio was found to be less than the theoretical figure of 2:1, the discrepancy being attributed to self-

Table 1. Observed Peak Intensity Ratios for the Resonance Doublets of O VI, Ne VIII, and A VIII Measured Photographically with the Aperture Limiter, and Photoelectrically

Doublet	λ (Å) (vac.)	Doublet intensity ratio		
		Photographic		Photoelectric
O VI	1031	Exposure 1	1.90 ± 0.10	
	1037	Exposure 2	1.84	1.86 ± 0.04
		Exposure 3	1.86	
Ne VIII	770	Exposure 1	1.96 ± 0.10	
	780	Exposure 2	1.95	1.90 ± 0.04
		Exposure 3	1.95	
A VIII	700	Exposure 1	1.91 ± 0.10	
	714	Exposure 2	1.91	1.90 ± 0.04
		Exposure 3	1.95	

absorption. These values were supported by the photoelectric measurements which were in close agreement, demonstrating the reliability of the aperture limiter method.

Discussion

It is not essential to arrange that exactly one-half of the grating is illuminated by each outer section of the beam, provided that the sum of the two outer intensities is equal to the intensity through the center section. Also it is not always the case that with equal illumination the densities of the outer sections of the image will be equal. This only occurs at wavelengths where the grating efficiency is uniform over the whole surface. At other wavelengths the reflectivity may vary over the grating area, in which case the density of one outer section may be higher or lower than that of the other. Such variations do occur with the particular grating in use, the maximum difference between the outer densities being approximately 25% at λ 600 Å. Figure 4 shows the Zeta spectrum in the region of the A VIII doublet, using argon and oxygen as trace elements in a deuterium discharge, and illustrates the division of the spectral line image into three sections.

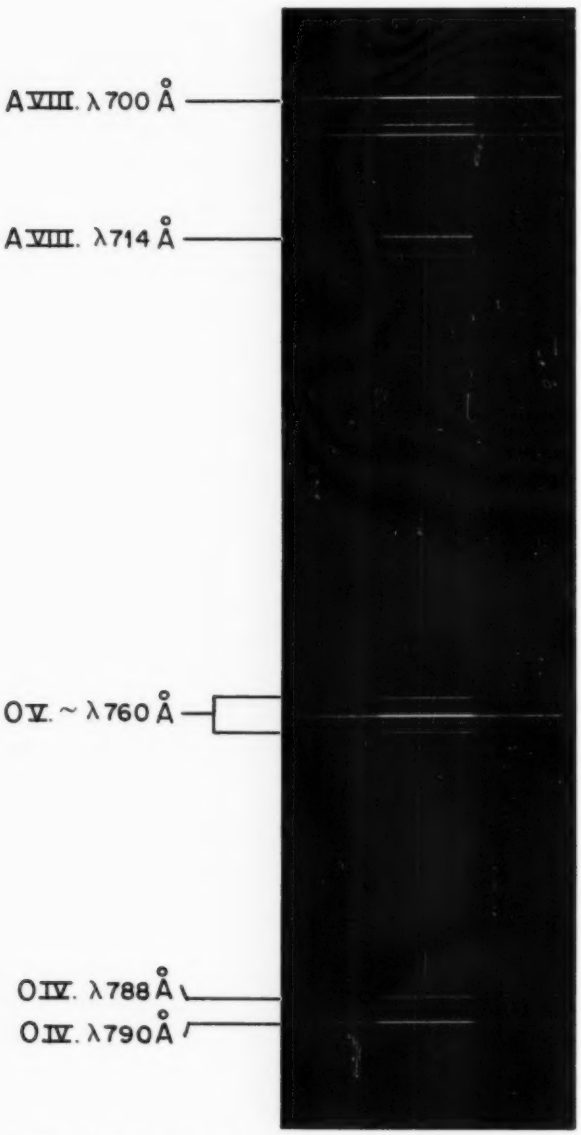

Fig. 4. Part of the Zeta spectrum in the vacuum ultraviolet, using oxygen and argon as trace elements in a deuterium discharge, illustrating the stepped intensity distribution in the spectral lines.

The experimental accuracy for single measurements of the half-intensity width of the center profile is ±5% when working on the straight part of the characteristic curve, when the outer densities differ by less than 10%. With density differences of 25% the error is approximately ±10%, these figures having been obtained from the observed scatter of experimental values, and from measurements with characteristic curves constructed as described previously for the spectral doublets, but used at slightly different wavelengths ($\Delta\lambda \simeq 100$ Å) as approximations. For a difference between the outer densities of 50% the accuracy of a half-width measurement is estimated, using an approximate curve, to be ±25%.

By means of a suitable number of exposures with a small intensity difference between each, the aperture limiter can be used to construct characteristic curves to cover the useful range of densities of a particular emulsion in the vacuum ultraviolet. The procedure is tedious, however, and the measurements at the threshold and saturation levels would be less accurate than those on the linear part of the curve.

The apparatus has been used so far only with the Zeta discharge, which corresponds closely to a spatially uniform source over the area viewed ($\sim 4 \times 3$ cm^2). This gives a uniform intensity distribution along the entrance slit throughout the spectrum. This distribution should of course be determined for each source used, and any necessary corrections applied.

The author is indebted to R. Wilson for his guidance and advice, and to W. M. Burton for helpful discussions and suggestions.

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A New Apparatus for Light Scattering Studies

H. G. Jerrard and D. B. Sellen

An instrument which is suitable for investigating the light scattering properties of macromolecules in solution in the angular range 20° to 160° is described. A null modulation method is used to measure the ratio of the intensity I_θ of the light scattered at an angle θ to the direction of the incident light to that (I_0) incident on the scattering volume. This is accomplished by attenuating I_0 until it equals I_θ, this condition being found by an electronic detector. The value of I_θ is known from a calibration experiment. Details are given of the optical arrangement, the detector, and the calibration and method of use of the apparatus. Adequate sensitivity, accuracy, and stability are demonstrated.

Introduction

A number of instruments designed for light scattering measurements have been developed in the last twenty years. Visual[1,2] and photographic[3] recording have been used but modern instruments usually employ photoelectric detection[4–16] which gives high precision and accuracy. In this paper an apparatus is described which, although developed primarily for detecting the small changes in scattered intensity that occur when macromolecular solutions are subjected to an applied electric field, is suitable for conventional light scattering measurements. The purpose for which it was designed necessitated higher sensitivity and accuracy than is possessed by other instruments. The instrument also has a wide angular range, an optical system producing a well defined, intense primary light beam of uniform cross section, a high degree of freedom from stray light, and good angular resolution. It is easy to operate.

Principle of Instrument

The function of a light scattering apparatus is to measure the ratio of the intensity of the light scattered from a solution in a cell to the intensity of the incident beam. In the present apparatus this is achieved by combining the two beams and allowing the resultant combination to fall on a single photomultiplier tube so that a null modulation method of detection can be realized. Such methods have been described by Hardy[15] and their merits discussed by Kovalevskii.[17] The principle is illustrated in Fig. 1. One beam, shown as the primary beam, is linearly polarized by a polaroid P_1 in a direction at 90° to that of the second beam which comprises the scattered light. The latter is polarized by P_2. Both beams traverse a polarizing disk P_3 which rotates with an angular velocity ω. If the intensities of the two beams, when incident on P_3, are I_1 and I_2 respectively, then the resulting intensity incident on the photomultiplier cathode is I where, ignoring absorption losses in the rotating disk,

$$I = \frac{(I_1 + I_2)}{2} + \frac{(I_1 - I_2)}{2} \cos 2\omega t. \qquad (1)$$

Thus there is a steady component equal to the average of the two incident intensities and an alternating component of twice the frequency of disk rotation and of peak to peak amplitude equal to the difference of the two incident intensities. When the intensities I_1 and I_2 are equal the alternating component disappears but only if the two beams are linearly polarized accurately at right angles.

The state of polarization of the scattered light is dependent upon the angle at which it is scattered. It is totally linearly polarized in directions at 90° to the incident beam, unpolarized for zero-angle scattering, and partially linearly polarized for all other angles. Thus the effect of P_2 will not only be to render the light incident on P_3 linearly polarized but will attenuate the beam by an amount which varies with the angle of scattering. To overcome this a quarter-wave plate is inserted in front of P_2 and set with its vibration directions at 45° to the plane of partial polarization. The linearly polarized component is thus turned into circularly polarized light so that no preferential direction of polarization exists, and hence the attenuation by P_2 of the linearly polarized component is th seame as

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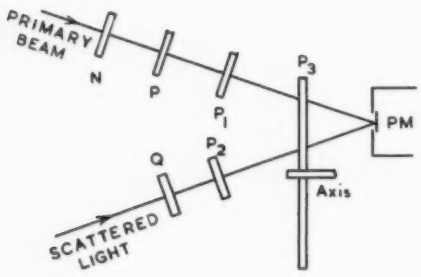

Fig. 1. Principle of apparatus. N—neutral filter, P—rotatable polarizer, P_1 and P_2—fixed polarizers, P_3—rotatory polaroid disk, PM—photomultiplier, Q—quarter-wave plate.

for unpolarized light. In practice the intensity of the primary beam is some 10^6 times that of the scattered intensity so that initially the primary beam intensity is attenuated by a neutral filter N in order to make the orders of magnitude of the two beams the same. Equality of intensity is then effected by rotating a polaroid P, the attenuation thus produced being proportional to $\cos^2\phi$, where ϕ is the angle between the vibration directions of P and P_1. The apparatus is calibrated in terms of ϕ.

Description of Apparatus

The apparatus is shown in Figs. 2 and 3. For the purpose of description it may be conveniently divided into the optical system, the electrical system, and the light scattering cell.

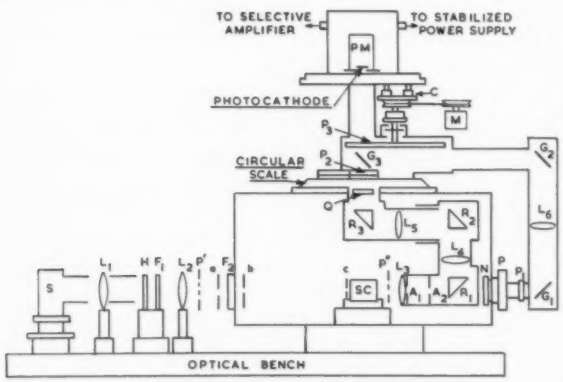

Fig. 2. Diagrammatic view of apparatus. S—mercury-arc lamp, L_1—condensing lens, H—circular diaphragm, F_1—heat absorbing filter, L_2—collimating lens, a, b, c—rectangular slits, F_2—interference filter, SC—light-scattering cell. The scattered light collecting system, which rotates about an axis through SC, includes lenses L_3, L_4, and L_5, diaphragms A_1 and A_2, reflecting prisms R_1, R_2, and R_3, quarter-wave plate Q, and polaroid P_2. The transmitted light collecting system, which is fixed, has a neutral filter N, polaroid P rotatable in divided circle, fixed polaroid P_1, reflecting plates G_1, G_2, and G_3, and lens L_6. P_3 is rotating polaroid driven by motor M; C—commutator, PM—photomultiplier. Polarizers can be placed on the optical bench at P′ and on end of collecting system at P″ for depolarization measurements.

A. The Optical System

This system consists essentially of a collimating arrangement to produce an intense incident beam and two collecting optical units mounted on a box. One unit, inside the box, brings the scattered light onto the photomultiplier and the second unit, mounted outside the box, collects the transmitted light. One side of the box can be removed to allow of easy access to the interior. Light from a mercury lamp S (G.E.C. 250 watts ME/D Compact Source) is condensed by a lens L_1 (focal length 10 cm; aperture 5 cm) upon a circular diaphragm H (diam 2.5 mm). The lamp is

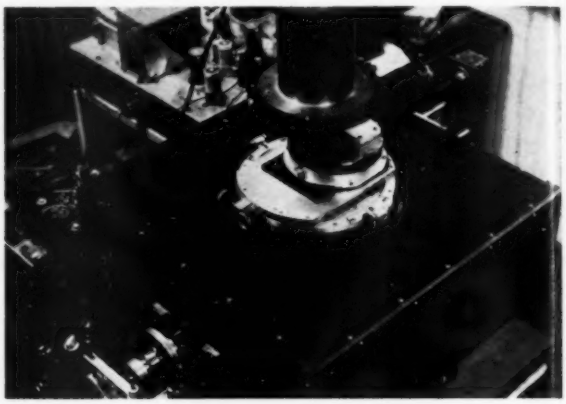

Fig. 3. Photograph of apparatus. At the center is seen the circular scale on top of the box below the photomultiplier housing. The transmitted light collector is on the right of the housing.

run on a stabilized dc supply. An image of H is produced near the center of the cell by a lens L_2 (focal length 6 cm; aperture 4 cm). Between H and L_2 is a heat absorbing filter, and between L_2 and the cell are an interference filter F_2 and three vertical rectangular slits a, b, and c each 2 mm wide and 1 cm high. This arrangement gives a well-defined uniform beam. A polarizer, whose axis can be adjusted to horizontal or vertical orientation, can be inserted between L_2 and a.

The scattered light is received by a collector unit containing prisms R_1, R_2, and R_3. This unit can be rotated about a vertical axis through the center of the box so as to receive light scattered at various angles in the horizontal plane, as in the apparatus of M'Ewen and Pratt.[9] The position of the unit relative to the incident beam of light can be read from a circular scale graduated in 0.5° intervals on top of the box. The light passes to the photocathode of the photomultiplier after total internal reflection in the prisms R_1, R_2, and R_3. All three prisms can be rotated about a horizontal axis and R_3 can also move about a vertical axis. The lens L_3 is focused for parallel light upon the circular aperture A_2 (diam 1.5 mm) which constitutes a field

stop. The distance L_2A_2 is 5 cm. The aperture A_1 (diam 4.5 mm) is an aperture stop. The angular resolving power of the unit is about 1°. Lens L_4 has its focus at A_1 and lens L_5 is placed so that an image of A_1 of about 9 mm diameter is formed on the photocathode which has a stop of 7 mm diameter in front of it. The image of A_1 is of uniform intensity and the stopping down of the photocathode area eliminates any error arising from any possible precession of the image about the axis of rotation due to misalignment. Thus the photomultiplier response is always independent of the angular position of the viewing unit. The unit may be extended between L_5 and R_2 to accommodate larger cells when necessary without altering the optics of the system. The quarter-wave plate Q and the polaroid P_2 are placed in the positions shown. The polaroid is of high quality and can be rotated from outside the box. It is adjusted so that the scattered light, after passing through the glass plate G_3, is linearly polarized in the plane of the diagram. Mica quarter plates mounted between glass cover slides are used, one for wavelength 5461 Å and another for 4358 Å. Provision is made for orienting the plate correctly. To ensure that a plate could not introduce an error greater than 1%, the wavelength for which it is quarter-wave must be correct to ±30 Å and its azimuth must not depart from 45° by more than ±0.5°. The plates used conformed to these limits and were selected after examination by the channeled spectrum method described by Jerrard.[18] For depolarization measurements a polaroid can be mounted on the viewing unit in front of the lens L_3, and the mounting was arranged so as to make it possible to transmit first the vertical and then the horizontal components of the light beam.

The incident light, after transmission through the cell, is received by the second collector unit which directs the beam to the photocathode by glass cover slips G_1, G_2, and G_3. These can be rotated about their horizontal axes and G_2 also about its vertical axis. The lens L_6 forms an image of c on the photocathode. The light leaving G_3 will be almost completely linearly polarized with its vibration direction perpendicular to the plane of the diagram. This linear polarization is assured by the insertion of the polaroid P_1 which is suitably oriented. The neutral filter N and polaroid P are placed as shown. P is mounted on a divided circle readable to 2 min of arc and which can be extrapolated to one minute. N was oriented at 45° to the primary beam so as not to reflect light back through the cell. This means that the transmitted light will be partially polarized, the vibration direction which is in excess being in the plane of incidence, i.e., in this case horizontal. Thus the attenuation as P is rotated is not proportional to $\cos^2\phi$, but to $f(\phi)$, where

$$f(\phi) = \cos^2\phi\{1 - [1 - \cos^4(i - r)] \sin^2\phi\}.$$

In this expression i and r are the angles of incidence and refraction, respectively. For $i = 45°$ and a glass of refractive index 1.52 as used here,

$$f(\phi) = \cos^2\phi(1 - 0.169 \sin^2\phi).$$

The beam is stopped down to a height of 2 mm after leaving N.

On leaving G_3 both beams pass through the rotating polarizing disk P_3 which serves simply as a modulator; the quality of the polaroid used for this is not important. The disk is driven by a small dc motor.

B. The Electrical System

Examination of Eq. (1) shows that the photomultiplier current consists of a steady component and an alternating component. In addition there is photoelectric shot noise associated with the signal, together with some dark current which is made up of a steady component and varying thermionic shot noise. Of these only the noise associated with the signal is significant. The detector unit is required to detect the alternating component and to determine the conditions when it is zero. For this purpose it is necessary to have a signal to noise ratio which is as high as possible. This ratio is proportional to the square root of the product of the light intensity, the photocathode sensitivity, and the time constant of the detecting system.

A block diagram of the system is shown in Fig. 4. An EMI photomultiplier type 9502 is used. This has good stability, an over-all sensitivity for an applied potential of 1650 volts of 2000 amp per lumen, and a dark current of 0.002 μa. Power is supplied from a stabilized supply. Output currents of up to 1 μa are obtained, which with a 10 megohm load give output potentials up to 10 volts peak value. The output is passed through a low gain selective amplifier having a Q factor that is variable from 4 to 20. The frequency of the alternating component that is to be detected is

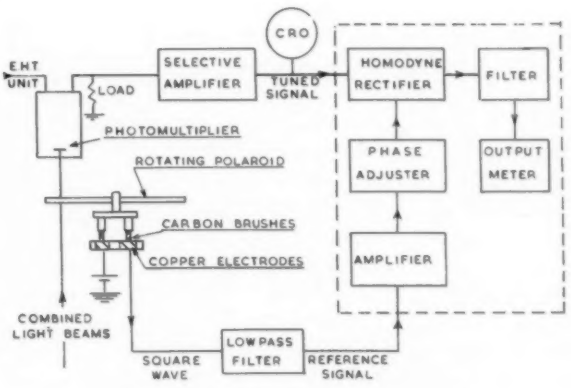

Fig. 4. Block diagram of electrical system.

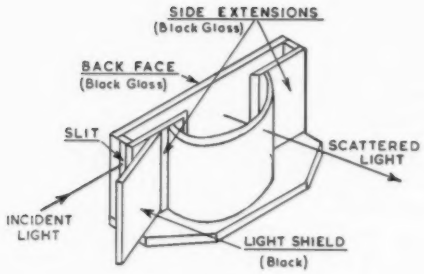

Fig. 5. The light-scattering cell.

110 cps, corresponding, for a Q factor of 20, to a time constant of about 0.2 sec. The amplifier output is displayed on a cathode-ray oscilloscope and also passes into a phase-sensitive (homodyne) rectifier. The homodyne is supplied with a reference signal and if this is in the same phase and has the same frequency as the signal from the selective amplifier, then the homodyne rectifier produces a dc output voltage which is proportional to the product of the amplitudes of the input and reference signals. This voltage is fed through a filter which removes voltages, due to noise or similar extraneous causes, which are not identical in frequency with the reference signal. The filter output is displayed on a meter. The filter can be adjusted for various times of response. The circuit used is a version of that given by Miller *et al.*[19] modified for the frequencies and response times required here. The latter are 1, 3, 8, and 40 sec. The reference signal for the homodyne has a frequency of twice the frequency of rotation of the polarizing disk P_3 and is obtained from a commutator mounted on the same shaft as P_3. This delivers a square wave of the appropriate frequency which then passes through a low-pass filter, an amplifier, and a phase adjuster so that the phase of the reference signal can be made the same as that of the signal to be detected. From the phase adjuster the signal is fed into the homodyne rectifier.

C. The Cell

The light-scattering cell shown in Fig. 5 is a semicylindrical type. The cylindrical part was ground from a piece of good quality glass so that there were no striations. The adhesive used is Araldite 103 with hardener 951. The side extensions are necessary as otherwise light scattered from the entrance window and suffering multiple reflections between the circular face and plane back face will emerge through the cell center into the viewing unit. With this cell arrangement these parasitic reflections are not visible. The use of black glass prevents internal reflections at the glass–air face of the back wall of the cell and reduces stray light in general.

Performance Data

Once the apparatus is calibrated, and after the liquid under examination is in the cell, it is only necessary to adjust to have no alternating component in the photomultiplier output. This is done by rotating P until no alternating component is visible on the C.R.O. trace, and the homodyne, when set for a small time constant, gives zero output. A finer adjustment for P is then obtained by increasing the values of time constant so that finally a reliable value for ϕ results.

Testing and Calibration

The geometry and alignment of the instrument were tested by measuring the angular dependence of fluorescent intensity exhibited by a dilute aqueous solution of fluorescein. The intensity should be independent of the angle at which it is seen.[20] Fluorescence was excited with light of wavelength 4358 Å and a yellow filter was placed in front of the viewing unit to stop the passage of any other scattered light and stray reflections. After correcting for cell geometry[21] by multiplying by $\sin\theta$, where θ is the angle between the incident beam direction and the direction of observation, the fluorescent intensity was found to be constant to within $\pm 0.35\%$. This was carried out with a time constant of 8 sec. This constancy of intensity does not mean, however, that the quarter-wave ($\lambda/4$) plate is functioning correctly since fluorescent light is unpolarized.

The correct setting and action of the $\lambda/4$ plate was checked, and the calibration of the apparatus was carried out by measuring the scattering and turbidity of a colloidal suspension of silica (Ludox*) in distilled water. This solution was centrifuged for 1 hr at 15,000 g and then put into the scattering cell using a hypodermic syringe which, after being filled, had a Millipore† cellulose filter unit attached to it. The filter had a pore size of 1.2 μ. Filtration alone of the Ludox was not sufficient. Polarizer settings ϕ were obtained for a number of values of θ. The measured background scattering of distilled water was subtracted and the resultant values multiplied by $\sin\theta/(1 + \cos^2\theta)$. A small correction was applied to allow for the fact that the lengths traveled in the solution in the cell by the incident and scattered light were different.[22] In the 60°–150° range the values of ϕ were constant to within 0.7%, indicating the correct functioning of the $\lambda/4$ plate. Below 60° a small rise (less than 4%) was detected and this was thought to be due to insufficient

* Prepared by E. I. du Pont de Nemours and Co., Delaware, U.S.A. English agents: Durham Raw Materials Ltd., London, England.

† Obtainable from Millipore Filter Corporation, Bedford, Massachusetts, U.S.A. English agents V. A. Howe and Co. Ltd., London, England.

clarification of the Ludox. The depolarization ρ_u at 90° was measured and extrapolated to zero concentration: its value was 0.0065 at 4358 Å.

The calibration constant C of the instrument is defined by the equation

$$\tau = \frac{2.303\,D}{l} = \frac{16\pi}{3} R_{90} = \frac{16\pi}{3} Cf(\phi)$$

in which τ is the turbidity, R_{90} the Rayleigh ratio at 90°, D is the optical density, l is the path length, and $f(\phi)$ is as previously defined. The turbidity of Ludox solutions of concentration 0.5% was measured with cells giving a value of l of 4 cm, in a Unicam SP500 spectrophotometer. In the range 4300 to 6000 Å, D was found to be porportional to λ^{-4}, which indicates that the measured values correspond to turbidity only and not to absorption.

A block of turbid glass for which $R_{90} = 5.3 \times 10^{-4}$ cm^{-1} at 5461 Å was used as a substandard to check the constancy of the value C. The standard deviation was never greater than 2% which was less than the accuracy with which C was determined.

Typical Results

A number of solutions have been studied with the apparatus described—a typical set of results being given by bovine plasma albumin. All measurements were taken at 20°C. This was dissolved in distilled water, centrifuged for 2 hr at 20,000 g and then passed through Millipore filters of sizes 1.2 μ and 0.1 μ. No dissymmetry of scattering was observed. From theory[12] the Rayleigh ratio R_θ, the concentration c (gm cm^{-3}), and the weight-average molecular weight M_w for a solution of refractive index n at wavelength λ in vacuo are related by the equation

$$\frac{Kc(1 + \cos^2\theta)}{R_\theta} = \frac{1}{M_w} + 2Bc,$$

where

$$K = \frac{2\pi^2 n^2 (\partial n/\partial c)^2}{\lambda^4 N_A},$$

in which N_A is Avogadro's number and B is a factor dependent on the type of macromolecule. A graph of $Kc(1 + \cos^2\theta)/R_\theta$ against c should give a straight line of intercept $1/M_w$ and slope $2B$. The value of $\partial n/\partial c$ was found from measurements with a Rayleigh interference refractometer. The graph is shown in Fig. 6 from which values of the slope and M_w of -3.5×10^{-4} and 69,000 respectively were found. The depolarization was measured ($\rho_u = 0.018$) and the molecular weight, corrected by use of the Cabannes factor,[23] was finally calculated to be 67,000. The results are in satisfactory agreement with those of Dandliker.[24]

The authors are grateful to A. M. Taylor for a number of suggestions and to S. W. Punnett for his advice on the electronics. Thanks are also due to J. H. Freeland who made most of the apparatus. One of us (D.B.S.) is indebted to the Department of Scientific and Industrial Research for the award of a research studentship.

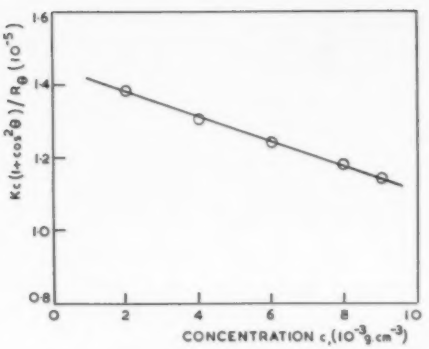

Fig. 6. Light scattering of bovine plasma albumin at 4358 Å and 20° C centrifuged and measured in water.

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Applied Optics — Patents

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3,015,988 Jan. 9, 1962 (Cl. 88-57)
Perspective alteration means.
H. S. Hemstreet. Assigned to General Precision, Inc. Filed Nov. 25, 1955.

A means for varying the perspective appearance of an object consists in projecting an image of the object through two variable anamorphosers and a zoom lens, all lying on a common optical axis. The correct settings and orientation of the various units are determined by a built-in analogue computer, and the units themselves are controlled electrically. R.K.

3,016,798 Jan. 16, 1962 (Cl. 88-57)
Compact achromatic telescope lens.
R. E. Lawrence. Assigned to the United States of America, Secretary of the Navy. Filed Oct. 9, 1958.

A very compact Cassegrain-type imaging system of low T-number is described, comprising two Mangin mirrors traversed in succession by the light. The front Mangin mirror acts also as a negative lens in the path of the entering beam, and the final image is formed in the space between the two mirrors. The whole system is mounted behind a thick concentric dome which aids in the aberration corrections, and an internal sunshade is provided to prevent light from reaching the image directly. R.K.

3,016,799 Jan. 16, 1962 (Cl. 88-57)
Wide-angle photographic or cinematographic objective.
G. Klemt and K. Macher. Assigned to Jos. Schneider & Co., Kreuznach. Filed Aug. 19, 1959 (in Germany Sept. 23, 1958).

A high-aperture (*f*/2) reversed telephoto objective is described, the back focal distance of which is greater than the focal length, for use on a single-lens reflex camera. The negative front component comprises a single positive element followed by a strong negative cemented doublet, and the positive rear component contains at least five airspaced elements. The space between the two components ranges from 40 to 50% of the total length of the system. R.K

3,018,688 Jan. 30, 1962 (Cl. 88-57)
Projection optical system.
J. D. Hayes. Assigned to Bausch & Lomb, Inc. Filed March 28, 1960.

A four-element objective is described, covering a semifield of 17° at *f*/2.5, which is composed entirely of nonbrowning glass for use at finite conjugates in an area of intense gamma radiation. The lens consists of two positive elements of crown glass, the second being of meniscus form, followed by a strong negative element of dense flint glass, and a positive crown element in the rear. R.K.

3,018,689 Jan. 30, 1962 (Cl. 88-57)
Optical system for electro-optical switching apparatus.
D. M. Saxe. Assigned to Bausch & Lomb, Inc. Filed May 28, 1959.

A highly-corrected 6-element lens is described, intended for use at 3× or 4× reduction, to project a very sharp image of a cathode-ray tube screen on to a coded pattern of dots on a glass plate in an electro-optical switching system. The lens contains two meniscus-shaped positive elements surrounding a central stop, outside of which are mounted a pair of thick meniscus-shaped cemented doublets. All the glasses used are chosen to transmit ultraviolet radiation between 3800 and 4200 Å, and there is no vignetting at *f*/8 aperture over a semifield of 25°. R.K.

3,020,804 Feb. 13, 1962 (Cl. 88-57)
Optical objective.
A. Cox and I. C. Sandback. Assigned to Bell and Howell Company. Filed Dec. 8, 1958.

A four-element objective of *f*/3.5 aperture is described, which covers a semifield of 25° and contains a provision for making a small adjustment in focal length by varying the rear airspace. The front element is biconvex, the second biconcave, and the remaining two elements are positive and of meniscus shape. The field is said to be flat and free from distortion. Three numerical examples are given. R.K.

Readers' attention is drawn to the April issue of *International Science and Technology*, featuring The New Optics, a survey by Harold S. Stewart. Also to the article entitled Vision of the Future: Spectacular Things Are Happening in the Sphere of Optics, by J. Richard Elliott, Jr., appearing in the March 19th issue of *Barron's*.

REFEREES

The following people referee papers submitted to APPLIED OPTICS from time to time, and the Editors wish to acknowledge with gratitude this service:

H. H. Allen, Jr., G. F. Aroyan, A. V. Baez, J. G. Baker, S. S. Ballard, R. Barakat, R. B. Barnes, E. Barr, E. S. Barr, A. M. Bass, J. R. Benford, L. E. Bergstein, B. H. Billings, L. S. Birks, W. S. Boyle, F. F. Byrne, H. Cary, R. M. Chapman, L. H. Chasson, C. H. Church, K. C. Clark, G. W. Cleek, V. J. Coates, R. J. Collins, W. A. Craven, Jr., A. Danti, J. A. Dobrowolski, K. Dressler, M. Dreyfus, W. G. Driscoll, S. Q. Duntley, D. Dutton, D. F. Eggers, Jr., R. S. Estey, W. Fastie, D. P. Feder, J. S. Garing, N. Ginsburg, G. E. Gross, F. F. Hall, Jr., G. B. Harrison, L. W. Herscher, M. Herzberger, I. C. Hisatsune, R. E. Hopkins, G. A. Hornbeck, E. O. Hulburt, R. S. Hunter, W. L. Hyde, J. A. Hynek, S. S. Impiombato, R. C. Jones, K. Innes, J. A. Jamieson, L. D. Kaplan, S. Katz, J. W. Kemp, K. G. Kessler, J. I. F. King, R. Kingslake, W. F. Koehler, N. Kriedl, E. W. Kutzscher, J. Lambe, E. V. Lowenstein, D. J. Lovell, T. K. McCubbin, R. K. McDonald, R. H. McFee, J. R. McNally, Jr., R. P. Madden, A. D. May, A. B. Meinel, P. E. Mengers, L. H. Meuser, D. F. Nelson, P. Nolan, R. A. Oetjen, J. Parsons, F. H. Perrin, G. N. Plass, E. K. Plyler, H. D. Polster, R. Potter, R. W. Powell, D. Richardson, D. W. Robinson, D. Z. Robinson, N. Rosenberg, J. A. Sanderson, J. B. Saunders, A. L. Schawlow, B. F. Scribner, J. H. Shaw, W. Sinton, F. S. Smith, E. Snitzer, V. J. Stakutis, O. N. Stavroudis, S. Sternberg, H. S. Stewart, B. Stoicheff, G. W. Stroke, R. E. Stroup, R. Tabeling, R. M. Talley, Y. Tanaka, R. Tousey, A. F. Turner, G. A. Vanasse, M. E. Warga, J. U. White, B. W. Wild, P. G. Wilkinson, P. A. Wilks, Jr., V. Z. Williams, D. E. Williamson, M. K. Wilson, W. Wolfe, E. M. Wormser, N. Wright, H. W. Yates, M. Zelikoff, and G. J. Zissis.

The Production of Circular Disks of Known Diameter for Calibration Purposes in High-Resolution Microscopy

W. N. Charman

The errors involved in dimensional measurements with the microscope are discussed, together with their reduction by calibration with objects of known size. A method is described for the preparation of disk objects from spheres of known diameter, using a series of evaporated thin films.

Introduction

The microscope provides one of the most widely used methods for determining the dimensions of small, nonperiodic objects, the measurements being made on the magnified image it produces. The scale of the magnification is normally found by replacing the object with one of known period, such as a stage micrometer. If the image of a particular object were formed under the laws of geometrical optics, then its boundary would be sharply defined and accurate determinations of the object dimensions would be possible. Diffraction, however, causes the edges of the image to display a gradation of light intensity, whose form depends upon the physical dimensions and optical properties of the object, the numerical apertures of the microscope condenser and objective, and the wavelength of the light employed. The relationship between the geometrical image of the edge and this intensity gradient has been determined theoretically for only a few objects under a limited number of optical conditions. Moreover, such results are generally only useful where the image intensity profile is recorded photoelectrically, since in visual observations the subjective brightness distribution does not normally correspond in a simple quantitative way to the physical intensity distribution.

An error of uncertain magnitude thus arises in all dimensional measurements made on isolated objects with the microscope, this error depending upon which point in the intensity gradient is chosen as representing the edge position. The criterion used in making this choice may vary considerably with the particular mode of measurement employed and, during visual observations, with the particular observer. The difference that generally exists between the measured size and the true size, due to the edge position selected not coinciding with the true geometrical image of the edge, has been pointed out by several authors, notably Loveland[1] and Welford.[2] Although these boundary effects are absent with periodic specimens, when the objects are nonperiodic in form their true size can only be obtained if it is possible to determine the magnitude of the edge errors by using objects whose dimensions are known. Without such a calibration, sizing errors of the same order of magnitude as the resolution limit of the microscope objective employed are usually given. While an increase in the numerical aperture of this objective tends to reduce the sizing error, the resolution limit of an oil-immersion objective used in the visible spectrum is still about 0.25 μ, so that the proportional error in measurements of object dimensions of less than 5 μ remains considerable. Since the microscope is often required to measure objects in the size range 0.5 to 5 μ, it is highly desirable that the errors involved should be reduced.

Ideally, if a range of objects were available, of known dimensions but of the same form and optical properties as the specimens to be sized, then a calibration curve of measured size against true size could be plotted for a particular set of optical conditions and used to give the true size of unknown objects under the same conditions using the same edge criterion.

In practice, such ideal test objects can rarely be found, but much can be gained by using objects of simple form such as spheres, cylinders, strips, and disks, whose shape often approximates to that of the specimen to be sized. For practical reasons it is desirable that any such test objects should be reasonably

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easy to obtain and should not themselves require extensive size calibration before use. Since only the electron microscope is capable of providing an accurate assessment of object dimensions and shape in the micron and submicron range, the question arises whether any of the test objects used in electron microscopy for size calibration are suitable for use with the optical microscope. One outstanding example immediately presents itself: the range of monodisperse polystyrene spheres manufactured by the Dow Chemical Co. of Michigan, these having found wide use as substandards in electron microscopy. Bradford and Vanderhoff,[3] in an extensive series of measurements of the spheres against a diffraction grating replica, using an electron microscope, found that the diameters of the ten groups of spheres lay between 0.088 and 1.171 μ, the diameters of each batch being uniform to within about 1%. More recently, two extra groups of spheres of mean diameters 1.83 and 2.79 μ have become available. Clearly the whole range provides admirable material for the production of test objects for high-resolution optical microscopy.

Under some circumstances, the spheres themselves, in a suitable mounting medium, may be useful as test objects, but objects of greater contrast are more often required. Slater[4] has described a method of producing such objects in the form of circular transparent apertures in an opaque aluminum film, these having the same diameter as the spheres. The plastic spheres, distributed on a clean microscope slide, were shadowed at normal incidence with evaporated aluminum, circular holes being given on removal of the spheres. Slater found during electron microscope studies of the resultant apertures that their diameter was equal to that of the spheres to within $\pm 1.5\%$.

Useful though such test objects may be, many of the specimens which are to be sized in practice appear dark in a bright field. In particular this is the case with samples of dust extracted from mine air, of which the National Coal Board counts and sizes many thousands, the present work having been connected with this program. It was therefore felt that there would be considerable advantages in extending Slater's basic evaporation technique, to produce opaque disks of the same diameter in a transparent surround, using the same plastic spheres. Optical microscope studies of disks made by the method developed have shown that their quality is comparable to that of apertures produced by Slater's technique.

Method

The disks are prepared as follows: A few drops of a dilute suspension of spheres (about 10^6/cc) of the required diameter are spread on a clean microscope slide and allowed to dry. A film of rock salt followed by an opaque layer of silver is then evaporated at normal incidence onto the slide at a pressure of about 5×10^{-5} mm of mercury. The slide is then gently slid into distilled water where the rock salt layer dissolves, so that, with care, the silver film containing apertures which are accurate projections of the spheres floats off in one piece and can be caught on a second clean microscope slide.

The silver film is allowed to dry and any spheres that have not already been removed during the floating off process are gently brushed or blown off, their removal being checked with a dry 4 mm microscope objective. A few scratches made in the film at this stage facilitate later focusing on the plane of the disks. A second opaque layer of silver is next evaporated on top of the first film, this new layer adhering strongly to the glass where apertures or scratches exist in the first film. The latter adheres weakly to the slide, since it was floated on. Thus, when a gentle current of distilled water is allowed to fall onto the slide, the first silver layer comes away easily, taking with it all the second film except for those parts which adhere directly to the glass. Accurate disks are therefore obtained with additional streaks of silver for focusing purposes.

The various stages in the process of disk preparation are shown diagrammatically in Fig. 1, while Fig. 2 shows a typical field of 1.171 μ disks, taken with a 1.28 N.A. objective. The high quality of the disks is apparent. Photoelectric scans of the intensity profiles of the disks, images show a standard deviation in half-width that is no larger than the standard deviation from the mean diameter of the original spheres. Although no electron microscope investigations have yet been made, it is probable that the quality of the disks approaches that found by Slater for his apertures.

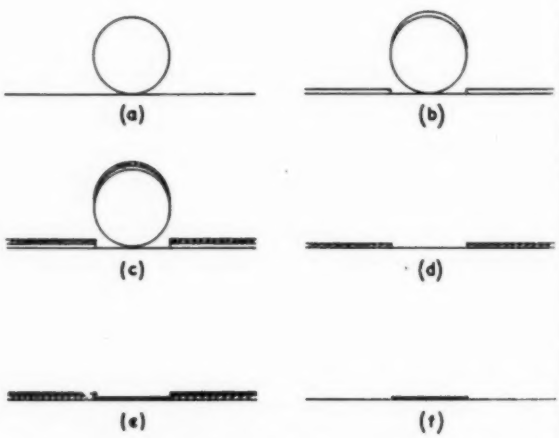

Fig. 1. Making opaque disks: (a) polystryene sphere on microscope slide, (b) rock salt evaporated on, (c) silver evaporated on, (d) silver removed by dissolving rock salt in water and settled on fresh slide, (e) more silver evaporated on, (f) first silver layer washed off leaving opaque silver discs equal in diameter to original spheres.

Discussion

It is clear from Fig. 1(c) that, if the original spheres are to be correctly profiled, then the combined thicknesses of the rock salt and silver layers must be less than the radius of the spheres. Monitoring of the rock salt thickness is a little difficult, since its refractive index (1.544) closely matches that of glass, but it can easily be controlled to about 1000 Å. The first silver layer must have a thickness which is equal to or greater than that of the second layer, so that, if the latter is to be made opaque, the first layer must at least be 1000 Å thick. The sphere radius must therefore exceed 2000 Å for correct profiling and accurate disk production, which, allowing a slight safety factor, means that the minimum diameter of the disks that can be prepared is about 5000 Å or 0.5 μ. If the rock salt evaporation could be rendered unnecessary, a corresponding reduction would be given in the minimum size of the disks that could be prepared. In principle this could be done by coating the slide with a film that was insoluble in water but highly soluble in some other solvent. The spheres would then be distributed on the slide in the normal way and shadowed with silver, the silver film being floated off by dissolving the original film in the solvent. However, attempts to find a suitable combination of film and solvent have so far been unsuccessful.

Since, in practice, a finite source–substrate distance and source size are used during the initial evaporations, the transparent apertures produced in the first silver film are not perfectly sharp-edged but are surrounded by a penumbra. In the arrangement used experimentally, the films were prepared in an Edwards 12E coating unit, a 60-cm belljar, manufactured by James A. Jobling and Co. of Sunderland, being used to give a source–substrate distance of about 45 cm. The source was restricted to a disk of approximately 6 mm diameter by suitable shaping of the molybdenum boats from which the evaporations were made, so that the calculated width of the penumbra round the sphere profiles in the first silver film was about 1.3% of the sphere radius. When the second silver evaporation was made through these apertures, the diameter of the disk that was in contact with the slide was therefore approximately 0.7% smaller than that of the original sphere. Since this is of the same order of magnitude as the standard deviation in diameters of the spheres themselves, this effect was not serious. Even with the 25 cm source–substrate distance available on most commercial coating plants, the width of the penumbra is below 3%, so that the errors in the size of the test objects will remain small. There is moreover some evidence for believing that the first film may fracture halfway through the penumbrated area, with a corresponding decrease in the error in disk size. In this connection it may be noted that, providing the floated-off silver film lies in good contact with the second slide, there appears to be no raggedness at the edge of the disks that would indicate irregular tearing of either of the films, in spite of the comparatively rough treatment they receive.

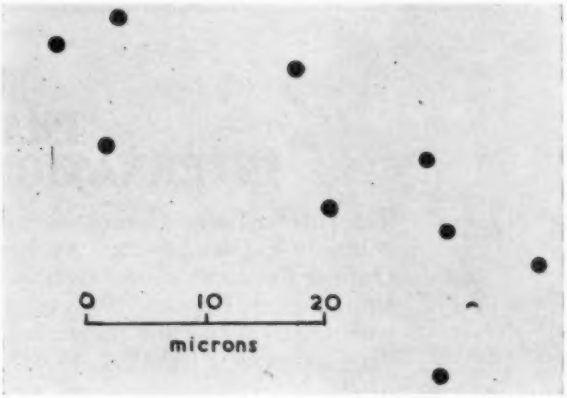

Fig. 2. 1.171 μ diameter disks.

For most purposes the fact that the objects are short cylinders rather than disks is not of great importance. Their thickness (about 0.1 μ) is still less than the depth of focus of the highest aperture microscope objectives, a fact which makes them easier to use as test objects than objects of greater thickness where the plane of focus is harder to define.

Although the technique as described has referred exclusively to the production of opaque disks, partially transmitting disks can be prepared by reducing the thickness of the second silver film, or pure phase objects can be made by replacing this film with a suitable evaporated dielectric.

Disks produced by this method have already been found useful for investigations into the accuracy of visual measurements of size with the microscope. Further experimental work is proceeding to compare the form of disk images under various optical conditions with theoretical predictions.

Acknowledgment is made to the National Coal Board for a grant in aid of this research. The opinions expressed are those of the author and not necessarily those of the Board.

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ICO SIXTH CONGRESS
MUNICH AUGUST 19–26 1962
IMAGE FORMATION AND VISION
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Image structure and image receiver
Behavior of the visual organ in relation to perception

There will be some ten general papers, including:

Image formation without silver (Eggert, Switzerland)
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Shorter papers will include those on

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Since physical as well as physiological, biological, and psychological problems will be discussed, a large number of participants is expected. Papers may be presented in English, French, or German. No plans have been made for publication of the proceedings; individual papers will be published in the usual way in the journals.

Notification of attendance should be sent to and full information obtained from Prof. Dr. Dr. H. Schober, 6. ICO-Kongress, Arnulfstr. 205(AEG-Haus), Munchen 19, Germany.

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See p. A18 for group flight information.

Refractometer Microscope

C. W. McCutchen

The refractometer microscope is simultaneously a microscope and a critical angle refractometer. It enables the user both to observe the shape and to measure the refractive index of the component areas of a flat surface. A prototype has been built.

Introduction

The refractometer microscope is an instrument for studying flat surfaces. It provides a picture of the surface in terms of the refractive index of its component areas. By use of an adjustable stop, the refractive index of any part of the specimen surface can be measured to an accuracy which is ultimately restricted only by diffraction limitations.

Principles

The specimen surface is placed against the first element of the microscope's objective lens, either by direct contact or by means of an immersion fluid. If N_s is the refractive index of the specimen and N_0 that of the first element of the objective, then any light crossing the interface from specimen to objective at a particular point will be within a cone, henceforth called the permitted cone, with half angle defined by the relation

$$\sin\alpha = \frac{N_s}{N_0}. \tag{1}$$

If this cone is to be entirely filled, the illuminating cone of light within the specimen must extend all the way to grazing incidence.

If the objective contains a patch stop which obstructs a cone of half angle α_p as measured at the interface, then light emerging from specimen points whose refractive index is less than $N_0 \sin\alpha_p$ will be entirely obstructed. Areas in the specimen will appear light or dark depending upon whether their refractive index is greater or less than $N_0 \sin\alpha_p$. The greater the margin by which N_s exceeds $N_0 \sin\alpha_p$, the thicker will be the hollow cone of light which passes the stop and the brighter the area will appear. If $N_0 \sin\alpha_p$, the refractive index cut off, is to be variable, the patch stop must be adjustable so as to vary α_p.

In order that the stop define the same cone angle for all points in the field of view it is necessary that the stop lie in the back focal surface of the objective.

From Eq. (1) the highest refractive index which can be measured is given by $N_0 \sin\alpha_{max}$, where α_{max} is the largest half angle which the optical system will pass. This is just the numerical aperture, which should therefore be as high as possible.

The Instrument

The requirements mentioned above have been met fairly well in the arrangement shown in Fig. 1. It is not the only possible system, but it is a workable one, especially in regard to the adjustable stop, which might have been expected to be a difficult problem.

The first element is an Amici sphere (a sphere cut off flat at its inner aplanatic point) made of Eastman Kodak E K 450 glass. This glass was chosen because it combines a refractive index of 1.804 with reasonable resistance to chemical attack. To provide the remaining convergence the Amici sphere is followed by the reflecting objective described by Dewhirst and Olney[1] which has a numerical aperture of 0.5. If it had a numerical aperture of 0.56 it would catch all the light from the Amici sphere and the over-all numerical aperture would be 1.804. As it is, it limits the over-all numerical aperture to 1.63. This lens has a working distance of 17 mm which allows enough room for the Amici sphere and also for the stop and illuminating mirror which must be placed behind it.

An Amici sphere has a back focal surface of roughly, though not exactly, ellipsoidal shape, defined by

$$\Delta = \frac{N_0^2(1 - \sin^2\gamma)}{N_0\sqrt{1 - \sin^2\gamma} - \sqrt{1 - N_0^2\sin^2\gamma}}, \tag{2}$$

which is derived in the Appendix. Figure 2 illustrates this surface for $N_0 = 1.8$ and also defines Δ and γ.

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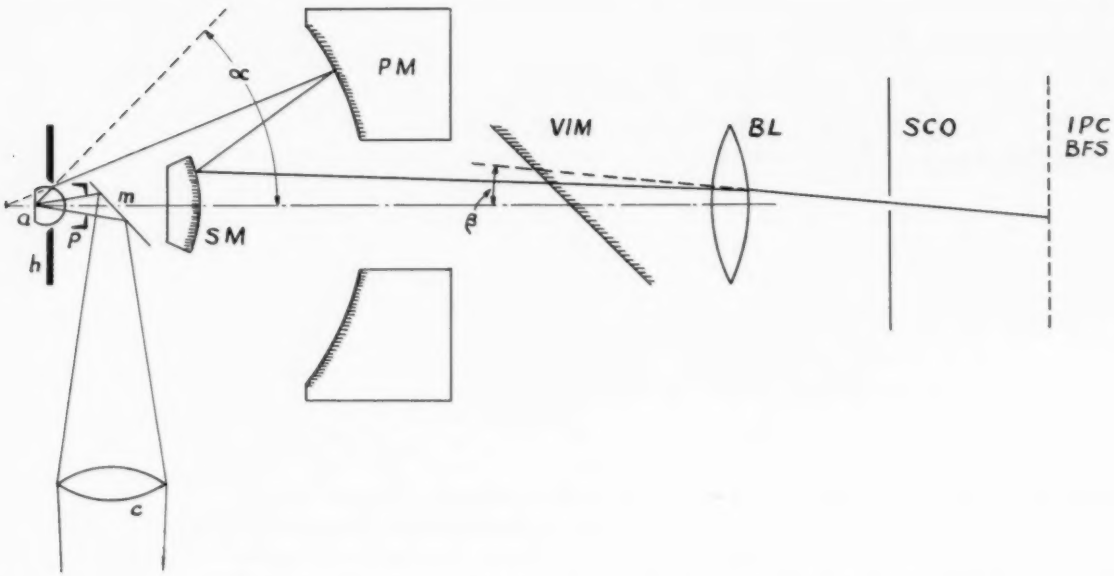

Fig. 1. General arrangement drawing. The instrument is shown with the Bertrand lens in use. Upon removal of components BL and SCO the image of the specimen surface falls upon IBPCFS. a—Amici sphere, c—condenser, h—hole stop, m—illuminating mirror, p—patch stop, PM—primary mirror of reflecting O.G., SM—secondary mirror of same, VIM—vertical illuminating mirror (unsilvered), BL—Bertrand lens, SCO—stop conjugate to specimen surface, IPCBFS—image plane conjugate to back focal surface. To save space in the drawing the microscope tube has been greatly foreshortened.

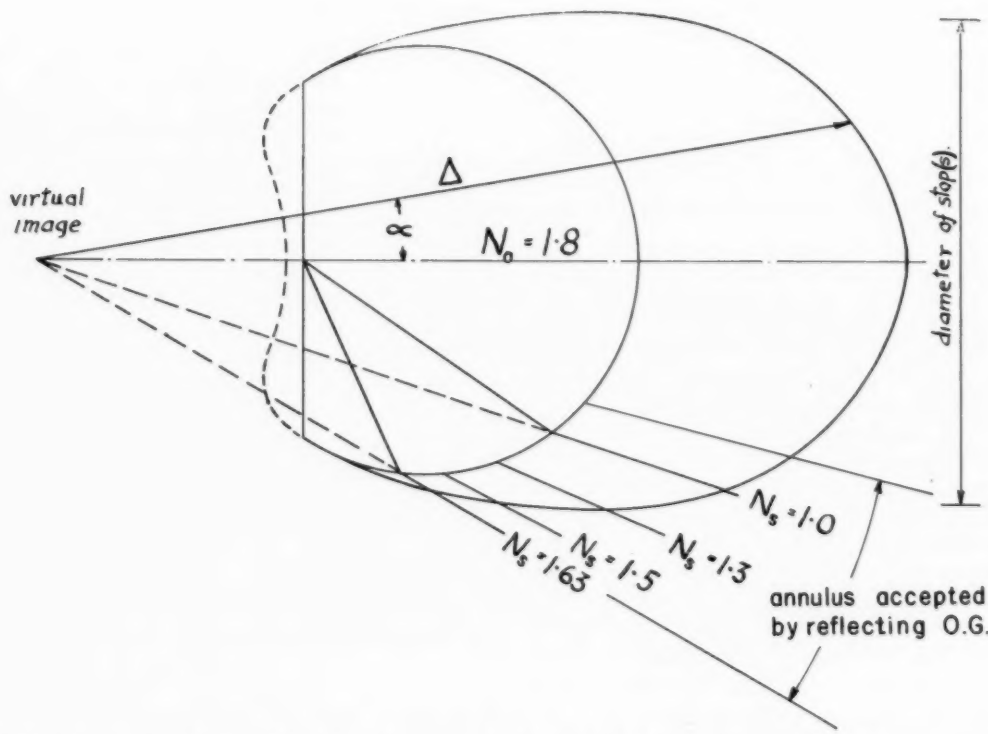

Fig. 2. The back focal surface of an Amici sphere with refractive index 1.8. Included are the edges of permitted cones corresponding to various specimen refractive indices.

Note that the portion of the surface which corresponds to useful specimen refractive indices (1.0 up to the instrumental limit of 1.63) is quite well approximated by a cylinder. The stop is thus of constant diameter, and is adjusted by being moved axially.

If it were thin and not too absorbing, the specimen could be illuminated by transmission; however, the method shown in Fig. 1 is more convenient and can deal with fairly highly absorbing objects. The light, partially focused by the condenser, is reflected by the diagonal mirror. It passes through a hole in the center of the stop (which the diagonal mirror effectively conceals from the observing side of the optical system) and into the Amici sphere which focuses it on the specimen. Once in the specimen it is diffused by variations in refractive index and produces the required omnidirectional illumination of the interface.

The diagonal mirror introduces the illumination at a point near the back focal surface. This is necessary because illumination and observation are associated with different zones of the aperture, and the back focal surface, or an image of it, are the only places where this separation is complete.

The Amici sphere has chromatic aberration and so requires the use of monochromatic light. It is necessary to decide on the sort of light to be used and then cut the flat so as to make the sphere aplanatic at the particular wavelength.

Operation

Figure 3 (taken at 55 cm tube length by objective projection, and using sodium light) is a view of damp chamois leather. The stop is set so as to pass light from water but not air. Water is bright and the leather fibers are brighter still. Figure 4 is the same picture except that the stop has been adjusted to reject just barely light from water and thus measure its refractive index. Note that the air–water boundaries are still visible as dim lines. This is because Snell's law only applies exactly when the dimensions of the interface are large (strictly, infinitely large) compared to the wavelength of light. A discontinuity behind the interface will let light through in directions which would otherwise be impossible.

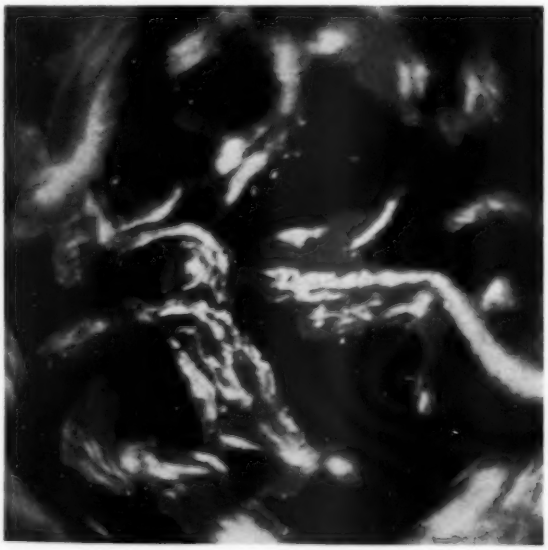

Fig. 3. Damp chamois leather viewed with the patch stop set somewhere between $N_s = 1$ and $N_s = 1.333$.

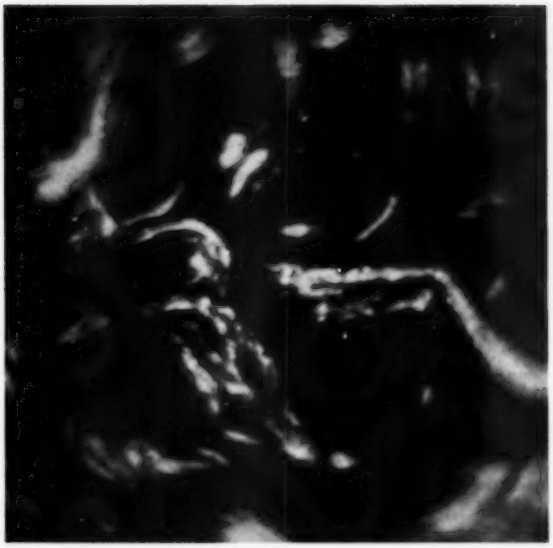

Fig. 4. The same view as in Fig. 3 (except that the water boundaries have shifted a little; this is a change in the specimen, not a property of the optics) but with the stop set to $N_s = 1.333$.

Once the stop is located in this manner it remains to extract the desired refractive index. The most obvious method is to measure the axial position of the stop. Then, if r is the radius of the stop and x its distance from the virtual image produced by the Amici sphere,

$$\sin\alpha = \frac{r}{\sqrt{r^2 + x^2}}.$$

This is not a convenient relation. Also, the accuracy of the measurement required is high.

A simpler method is to use a Bertrand lens to examine the back focal surface of the Amici sphere (see Fig. 1). The apparent diameter of the stop, which is easily measured with a graticule eyepiece, is proportional to $\sin\alpha_p$. If a fair proportion of the field of view is occupied by material of a single refractive index the Bertrand lens will reveal a bright disk whose outer edge is at the value of $\sin\alpha$ corresponding to the refractive index.

The effect of the Bertrand lens is to convert the instrument into a critical angle refractometer with circular symmetry.

Figure 5 shows the Bertrand lens picture corresponding to Fig. 3. The inner bright disk is formed by light entering from water, while the outer disk is contributed by the leather fibers which have a higher refractive index. The diffuseness of this disk probably arises largely from variations in the refractive index of the fibers though (as will be seen later) their small size is a contributing factor. The Bertrand lens picture coresponding to Fig. 4 would be the same except that the stop would just cover the water disk.

Figure 6 is the Bertrand lens picture for a specimen consisting of one patch of water and one of CCl_4. The diameter of the CCl_4 disk is, as expected, 1.463/1.333 times that of the water disk.

That the diameter of the image is proportional to $\sin\alpha$, in spite of the extreme curvature of the back focal surface of the Amici sphere, is shown by the following argument. As a consequence of the Abbe sine condition, light emerging from the center of the object will pass through the conjugate image point at an angle (see Fig. 1) such that

$$\sin\beta = k \sin\alpha,$$

where k is a constant of the system. If one imagines an infinitesimal stop at this image point and a screen beyond, then the screen will receive, by pinhole projection, an image, the radius of which corresponds (very nearly, as $\sin\beta \cong \tan\beta$) to $\sin\alpha$. If this stop is opened up, light originating from off-axis points will reach the screen. If this is correctly positioned an image will be formed of the back focal surface. Because the latter is highly curved, and because the reflecting objective is observing an object which is far from its normal focus, this image is imperfect, so the stop opening must be kept fairly small. Since this image necessarily contains contributions from the axial object point, for which we know that image radius is proportional to $\sin\alpha$, this relation must hold for all contributions with an uncertainty no more than that associated with the fuzziness of the image.

Resolution

As is clear from Figs. 5 and 6 the objective aperture is quite a thin annulus. The resulting diffraction pattern has much energy in the outlying rings, which is bad for observing complex objects. The narrower the annulus the more is the energy thus dispersed.

The effective aperture is not, as one might naively expect, the annulus lying between the stop and the edge of the permitted cone, but is the entire annulus outside the stop. This is because, as is shown by Fig. 4, discontinuities diffract light into the nonpermitted region. For good resolution the stop should be set so as to obstruct as little light as possible. This is verified by a comparison of Figs. 3 and 4 which shows both the air–water and the water–leather boundaries to be better resolved in Fig. 3. The inner part of the annulus still assists resolution of a boundary even when it accepts light from both sides, because the light originating in the region with higher refractive index is more intense. The improved resolution is accompanied by a loss in contrast, so a compromise is necessary.

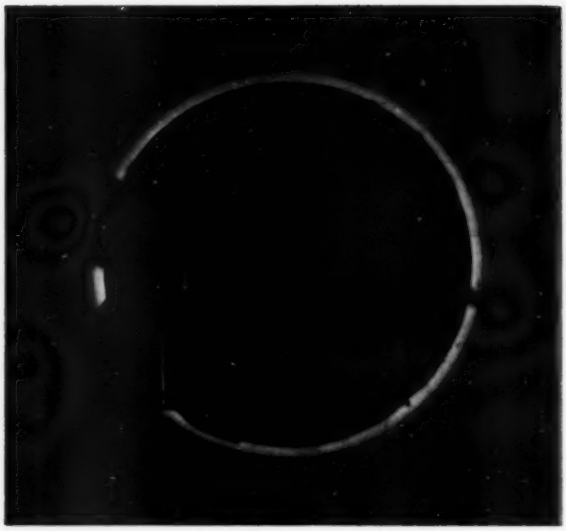

Fig. 5. Bertrand lens view showing the back focal surface of the Amici sphere when the latter is observing damp chamois leather under conditions similar to those in Fig. 3.

In these plates, the resolution is roughly about 1.5μ at the middle of the field. Whether this is the ultimate diffraction limit is not certain. The Amici sphere had its flat located at the inner aplanatic point by measurement rather than interferometry, so there may be spherical aberration.

The image quality deteriorates very rapidly with distance from the center. Certainly most of this deterioration is caused by severe field curvature, for the Petzval curvatures of the Amici sphere and the reflecting objective are both positive, while the object surface is uncompromisingly flat. (If the present Cassegranian reflecting objective were replaced by a Gregorian system it would be possible to make the Petzval sum zero). Such other aberrations as the system may have are masked by the field curvature.

Refractive Index

With the present instrument the precision of refractive index measurements is only to within about ± 0.005 units of refractive index. With a more accurately circular stop, more precisely centered, this should be greatly improved. This precision holds for all refractive indices

in the sample but the lowest. With that one exception the stop can be adjusted until the particular patch is as black as those of lower refractive index. For the patch of lowest refractive index there is no comparison and one is reduced to estimating how black black should be. Inevitably there will be some scattered light outside the permitted cone so black is not jet black and depends on the stop position even when the permitted cone is obscured. One is therefore reduced to finding the kink in the brightness versus stop position relation when the stop begins to pass the permitted cone. Even so the accuracy is to within about ± 0.01 and this will be improved with a more circular stop which will give a sharper kink.

The fact that it is possible to produce omnidirectional illumination may come as a surprise and, in fact, the illumination is probably not perfect. Fortunately the critical angle method is quite insensitive to a deficiency in the illuminating cone. If the half angle is only 89° the error in the refractive index value is only 0.015%, while to produce an error of 0.5% requires that the cone half angle be reduced to 84.24°.

For small specimen patches the precision is limited by diffraction, for, in reality, the permitted cone of light emanating from a finite patch does not have a perfectly sharp edge (in terms of angle; in position it is as uncertain as the dimensions of the patch, but this uncertainty disappears at the back focal surface).

If one considers the patch as an aperture in Fraunhofer diffraction (see Fig. 7) the uncertainty $\delta\alpha$ in the half angle of the permitted cone is of the order $\lambda/N_0 L\cos\alpha$ where λ is the vacuum wavelength of the light and L is the length of the patch. From Eq. (1)

Fig. 6. Bertrand lens view when the specimen was part water and part CCl_4.

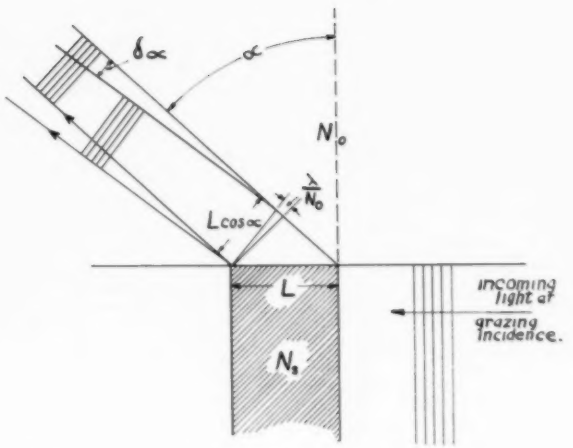

Fig. 7. Fraunhofer diffraction of the edge of the permitted cone produced by a patch of length L and refractive index N_s.

$$\frac{dN_s}{d\alpha} = N_0 \cos\alpha,$$

$$\delta N_s = \frac{dN_s}{d\alpha}\,\delta\alpha = N_0 \cos\alpha \frac{\lambda}{N_0 L \cos\alpha} = \frac{\lambda}{L}. \qquad (3)$$

This would suggest that a 10μ patch would give an error in N_s of 6%. Experimentally, however, a 10μ patch can be measured almost to the same accuracy as a very large one if one is careful to disregard the edges. This is not surprising because one would expect that the diffraction effects which cause the blurring of the edges of the permitted cone would be concentrated at the edges of the patch. Without a full-scale analysis of the problem one can only say that experiment indicates that the precision of measurement is the same for all patches which are big enough so that the diffraction lines marking their edges do not overlap.

Light Field Operation

If the specimen absorbs very strongly, the dark field method cannot be used because the illuminating light is absorbed before being sufficiently randomized. One then has to use light field illumination. A conventional vertical illuminator is used to project light backward through the annular observing aperture. It passes through the Amici sphere and meets the interface where it is or is not totally reflected according to the value of the refractive index of the specimen at that particular point. It then passes back through the optical system and forms an image which is complementary to the light field image—a specimen patch of high refractive index appearing dark.

The light field image has less contrast than the dark field image because, unlike transmission, refraction is never completely absent whatever the angle of incidence (except for the Brewster angle, which only affects one

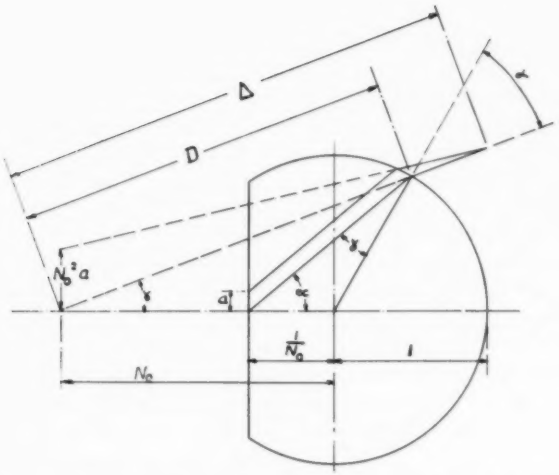

Fig. 8. The properties of the Amici sphere used in drawing the shape of its back focal surface.

polarity). Further, a refractive index measurement requires that the observer match the brightness of two bright areas rather than two dark ones, which is bad from signal to noise (i.e., contrast) considerations.

The contrast can be improved by fitting a hole stop of the same diameter as the patch. This, also, is adjusted by axial motion. It is set to cut off the outer portion of the aperture where the light is all totally reflected. Unfortunately this affects the resolution because the obstructed zone contains information in the form of absent light which has been removed by diffraction.

Third Dimension Effects

As well as requiring an interface of infinite extent, exact obedience to Snell's law requires that the regions in the sample be of infinite depth. When the depth of a region becomes comparable to the wavelength of light, barrier penetration and related phenomena will occur. However, there has not yet been sufficient experience with the instrument to be able to determine how annoying, or useful, these effects may be.

Another effect arising in the third dimension occurs when the specimen has a strongly reflecting discontinuity near the interface. In dark field operation this, if properly oriented, will reflect the incident illuminating light into the accepted annulus in one stage and thus bypass the diffusing process. In light field operation it can return to the optical system light which has penetrated the interface and would otherwise be diffused and absorbed. In both cases the result is a bright star which is easily recognizable because, as it is not at the interface, it is not in focus. In dark field operation this effect can be eliminated by using a patch stop in the condenser at the plane conjugate to the object. The illumination is thus in the form of a ring which surrounds, but does not shine directly upon, the field of view.

Uses

The instrument as described, with the Amici sphere cut off exactly at the inner aplanatic point, can be used for deformable surfaces which will mould themselves to the flat lens surface. Smaller objects can be placed upon a deformable backstop and pressed into contact. One or the other of these methods will permit examination of most biological materials. In fact the original purpose for which the instrument was made was to examine the rubbing surface of animal joint cartilage.

If the sphere is cut back further, and the difference made up with immersion fluid, one can examine specimens which are flat and polished. An obvious use in mineralogy is in measuring the refractive index of small component crystals in polished rock samples. Light field operation permits the use of polarized light.

Some applications may require magnifications of less than 100. Under these conditions the exit pupil, which is annular, becomes so large that if the observer keeps his eye on the axis he "sees" only the hole in the middle. In practice he moves his head slightly so as to center his eye on a part of the rim of the exit pupil. This probably does not improve the appearance of the image. A more elegant method is to set the objective for the image at infinity and then to look at it with a low power telescope. This telescope can be moved bodily sideways, with no deterioration in the ray-optical quality of the system. One can then place the rim of the annular exit pupil in the middle of the eyepiece. Loss in aperture does no harm at this low magnification.

One should be cautious about estimating the usefulness of the device on the basis of the performance of the prototype, for it was built of components which were either immediately available or easily made. A fully engineered version should be substantially better.

Appendix. Shape of the Back Focal Surface of the Amici Sphere

We shall investigate what happens to two parallel rays of light which leave the interface, one at the center and one a short distance away (Fig. 8). The radius of the sphere is taken as 1. The well-known properties of the Amici sphere provide all the information shown on the drawing. What is required is an expression for Δ in terms of γ which will give the shape of the back focal surface in polar coordinates centered at the middle of the virtual image.

The parallel rays are separated by $a\cos\alpha$ so they meet the surface of the sphere at points spaced $a\cos\alpha/\cos\gamma$ apart. They emerge from the sphere separated from each other by $a\cos^2\alpha/\cos\gamma$.

By similar triangles

$$\frac{\Delta - D}{a \cos^2\alpha/\cos\gamma} = \frac{\Delta}{aN_0^2 \cos\gamma},$$

so

$$\Delta(N_0^2 \cos^2\gamma - \cos^2\alpha) = DN_0^2 \cos^2\gamma,$$

where

$$D = N_0 \cos\gamma + \cos\alpha,$$

$$\Delta = \frac{N_0^2 \cos^2\gamma}{N_0 \cos\gamma - \cos\alpha}. \tag{2a}$$

In terms of sines

$$\Delta = \frac{N_0^2(1 - \sin^2\gamma)}{N_0\sqrt{1 - \sin^2\gamma} - \sqrt{1 - \sin^2\alpha}}.$$

Since, by Snell's law, $\sin\alpha = N_0 \sin\gamma$,

$$\Delta = \frac{N_0^2(1 - \sin^2\gamma)}{N_0\sqrt{1 - \sin^2\gamma} - \sqrt{1 - N_0^2 \sin^2\gamma}}. \tag{2}$$

That this is not an ellipse is shown by formally allowing α to exceed 90° in Eq. (2a). In Eq. (2) this means changing the sign in the denominator. The points thus plotted complete the curve around in front of the Amici sphere. This part of the curve, shown dotted in Fig. 2, is definitely not elliptical.

The author wishes to thank the Physics and Chemistry of Solids Subdepartment of the Cavendish Laboratory for financial support during the early stages of this work.

Reference

1. D. W. Dewhirst and M. J. Olney, J. Iron and Steel Inst. (London) **167,** 221 (1951).

Ian M. Mills (center) *Reading University, England,* Lomb Medallist 1960, then OSA President James G. Baker, and Mary E. Warga, OSA Executive Secretary
photo American Institute of Physics

Optics in France

G. Amat, A. Arsac, J. Brochard, J. Brossel, P. Connes,
L. Couture, P. Jacquinot, and A. Maréchal

Research activity in the optics field has been lively in France for a long time; the following names may be recalled: Fermat, Descartes, Fresnel, Arago, Cornu, Savart, Deslandres, Cotton, Fabry, Lyot, de Gramont, Cabannes. Even at the present time a relatively important number of research workers are dealing with optical problems; among the 550 physicists at the National Center for Scientific Research (CNRS), 125 are working in the field of spectroscopy and optics, and this is at least partly due to the fact that a larger part of the curriculum is still devoted to such classical subjects as optics. The present paper deals with optics in the usual sense and also with that area of spectroscopy that includes the regions outside the so-called luminous optics, i.e., from ultraviolet to infrared. It is divided into seven sections: (A) instrumental optics, (B) optics for radioastronomy, (C) spectroscopic instrumentation, (D) atomic spectroscopy, (E) solid-state spectroscopy, (F) molecular spectroscopy, and (G) microwave spectroscopy. In each section, a summary of present activity is given, omitting that which is well known or obsolete. A comparison of the above divisions and the authors' names will lead the reader to an unambiguous conclusion about writing responsibilities.

A. L'Optique Instrumentale

La conception des instruments d'optique nécessite des connaissances approfondies sur le mécanisme de la formation des images et sur les propriétés des récepteurs; leur réalisation fait appel à des études sur les matériaux, les techniques de surfaçage, les couches minces interférentielles, etc. Nous étudierons tour à tour les travaux de caractère général, et nous indiquerons pour terminer quelques réalisation pratiques.

I. La Formation des Images

(a) L'utilisation de la Transformation de Fourier

C'est P.M. Duffieux[1] qui a attiré l'attention des physiciens sur l'intérêt théorique que présentent les techniques de l'analyse harmonique pour l'étude des images optiques. Dans une série de publications, il a montré que la transformation de Fourier était utile non seulement pour l'étude de la formation des images en éclairage cohérent, mais également dans le cas de l'éclairage incohérent: il a mis en évidence dans ce dernier cas l'existence d'une fonction de transfert qui apparait sous la forme de la fonction d'autocorrélation pupillaire (si la pupille est circulaire cette fonction représente la surface commune à deux cercles). Un instrument d'optique devient ainsi un "filtre de fréquences spatiales" dont le fonctionnement est à comparer à celui d'une chaîne électro acoustique destinée à la transmission d'un son. On connait le rôle important que joue maintenant "l'optique de Fourier" et nous indiquerons quelques applications:

1. Les techniques "d'apodisation" proposées par P. Jacquinot[2] pour éliminer les franges latérales de diffraction dans l'image d'un point ont fait l'objet d'études théoriques approfondies par Madame B. Roizen Dossier.[3] Des résultats pratiques intéressants ont été obtenus en particulier dans le cas des systèmes à obturation centrale.

2. Le filtrage des images photographiques a été proposé par A. Maréchal et P. Croce[4] en 1953 et développé ultérieurement par divers chercheurs (en particulier par O'Neill aux Etats-Unis). Une image optique est une interprétation de l'objet par un instrument dont la fonction de transfert est invariablement une loi du type "passe bas." On peut améliorer cette image en lui faisant subir un filtrage compensateur que l'on peut effectuer en particulier à l'aide d'un montage en éclairage cohérent (fig. 1). La figure 2 montre un exemple de résultat obtenu à l'Institut d'Optique par J. Tsiujiuchi[5]: le texte (a) a été brouillé par défaut de mise au point et a donné le texte (b) difficile à lire. Le

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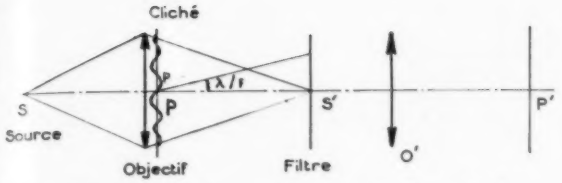


Fig. 1. Dispositif d'éclairage cohérent pour le filtrage des images optiques.

filtrage optique permet d'obtenir le texte (c) à partir de (b). On constate que la lisibilité en est nettement meilleure. Cette technique permet également d'améliorer le contraste de petits détails dans les images et d'en extraire ainsi toutes les informations utiles.

3. A. Blanc-Lapierre[6] et ses élèves ont apporté une contribution importante à la théorie de la cohérence partielle en montrant l'usage que l'on peut faire de la théorie des corrélations pour obtenir des résultats généraux établis par ailleurs par H. H. Hopkins et E. Wolf. Récemment le cas des objets de faible contraste, étudié par S. Slansky[7] a donné l'occasion de montrer que la théorie de la cohérence partielle permettait d'obtenir des résultats simples et directement utilisables par les microscopistes.

4. De nouveaux dispositifs permettant d'effectuer des pointés optiques de haute précision ont été proposés: (a) A. Arnulf et O. Dupuy[8] pour la détection de très faibles déplacements latéraux. (b) J. Simon[9] pour les pointés longitudinaux (on peut détecter une variation de chemin optique de $\lambda/1000$). (c) A. Maréchal, O. Dupuy, et M. Renault[10] pour la détection de très légères variations de chemin optique dans un montage dérivé de Zernike mais où l'objet est un objet périodique incohérent. La sensibilité est encore ici de l'ordre de $\lambda/1000$.

(b) Le cas des Objets Déphasants

Le contraste de phase a donné lieu en France à des recherches actives, depuis que B. Lyot l'avait utilisé pour le contrôle des pièces astronomiques. Les recherches récentes portent plutôt sur les techniques de contraste interférentiel et surtout sur celles qui utilisent la polarisation pour l'observation des "objets de phase" isotropes. M. Françon[11] et G. Nomarski[12] ont mis au point un certain nombre de dispositifs que l'on peut employer soit en microscopie, soit encore dans les souffleries aérodynamiques.

II. Les Materiaux Optiques

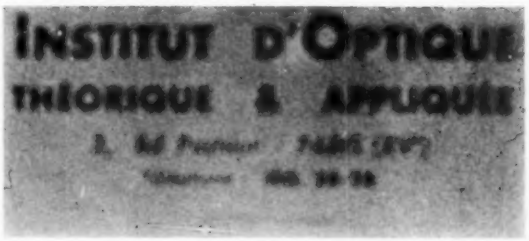
(a) Le Verre

Des recherches sur les propriétés du verre sont effectuées à la fois dans l'industrie (Saint-Gobain, Parra Mantois) et à l'Institut d'Optique, les travaux systématiques de Madame Winter[13] ont abouti d'ailleurs à la découverte de nouveaux types de verres (verres sans silicium par exemple).

(b) Les Couches Minces Interférentielles

Les techniques de calcul des couches minces ne sont plus l'objet de nombreux travaux mais les physiciens se préoccupent surtout de la structure physique des couches métalliques ou diélectriques: nature, dimensions et orientation des cristaux obtenus, en liaison avec les propriétés optiques, magnétiques ou électriques. Un effort important est fait actuellement pour étudier une même couche par diverses méthodes physiques: microscopie et diffraction électroniques, diffraction X, résistivité électrique, effet Hall, propriétés optiques; ces travaux sont principalement effectués sous la direction de P. Rouard[14] à Marseille, de F. Abeles,[15] et P. Croce[16] à l'Institut d'Optique. P. Croce et Mme M. Gandais[17] ont d'ailleurs mis en évidence la présence de fines franges qui accompagnent les raies de diffraction X, de certaines couches d'or régulièrement cristallisées. L'étude de ces franges permet d'obtenir

(a)



(b)

(c)

Fig. 2 (a) est le texte original (b) en est vue photographie brouillée et (c) est le resultat du filtrage optique de (b). Noter la lisibilité du terte et la résolution des traits sous le texte.

une valeur précise de l'épaisseur. Cette épaisseur peut également être obtenue par l'étude de la variation de fréquence propre d'un cristal de quartz.[18]

De nombreuses applications ont été mises au point; citons par exemple la fabrication de filtres interférentiels à couches multiples pour l'infra rouge (4 μ) avec une transparence supérieure à 0.7 et une demi largeur de bande inférieure à 0.1 μ.

(c) Les Réseaux Optiques

Les travaux de G. Stroke[19] au MIT, puis à l'Institut d'Optique de Paris ont permis de préciser l'origine des effets de "blaze" dans les réseaux; ces effets sont liés à la nature des conditions aux limites imposées à la surface du métal. D'autre part une machine à tracer munie du contrôle interférométrique pourra probablement permettre à la Société Jobin et Yvon de fournir des réseaux de qualité dans un très proche avenir.

III. Les Recepteurs de Rayonnement

Les progrés les plus remarquables ont été effectués dans le domaine des récepteurs photoélectriques, avec la mise au point de la caméra électronique de A. Lallemand,[20] dont l'usage est maintenant répandu en astronomie. On sait que ce récepteur d'images permet d'obtenir rapidement des images photographiques qui auraient demandé normalement des poses trés longues avec les émulsions courantes.

Deux laboratoires étudient d'autre part les propriétés de l'oeil: (1) Au Muséum Y. Le Grand et ses collaborateurs se sont consacrés à l'étude du mécanisme de la vision des couleurs, de l'acuité en vision périphérique, du seuil différentiel de luminance, etc.[21] (2) A l'Institut d'Optique A. Arnulf et ses collaborateurs[22] ont déterminé la fonction de transfert des fréquences spatiales, due à l'ensemble des propriétés de l'appareil optique et de la rétine. Des mesures de l'aberration sphérique produites par une double traversée du système optique ont pu être effectuées par la méthode de Foucault.[23]

IV. Quelques Réalisations

Nous nous bornerons à citer quelques instruments intéressants de réalisation récente.

(a) Objectifs Photographiques et de Cinéma—Les Zooms

L'évènement le plus important dans ce domaine est l'apparition des objectifs à focale variable, que l'on doit principalement à deux firmes:

1. La S.O.M. qui fabrique le Pancinor depuis 1950. Dans cet objectif on déplace d'un même mouvement deux groupes de lentilles divergentes, ce qui rend la réalisation mécanique relativement simple. On arrive ainsi à des rapports de longueurs focales de 5 à 1 dans les modèles courants. Le Pancinor a reçu le Technical Award de l'"Academy of Motion Picture" en 1957.

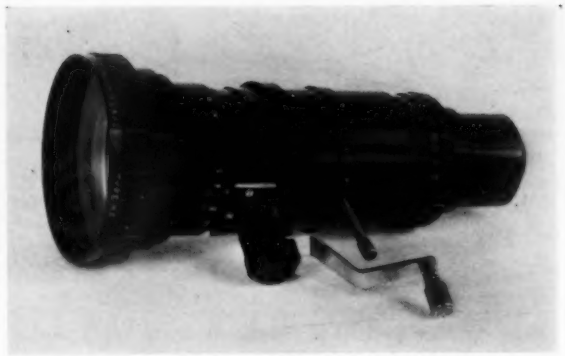


Fig. 3. L'un des nouveaux objectifs á focale variable (Zooms) Angénieux pour le film de 16 mm; le rapport des distances focales extrêmes est de 10.

2. La société Angénieux qui réalise des zooms dans lesquels les déplacements relatifs sont obtenus à l'aide de cames; ceci permet de maintenir l'image fixe avec un rapport de longueurs focales plus important: on atteint actuellement le rapport 10 entre les focales extrêmes. Voici les caractéristiques principales d'un objectif de prise de vues pour le 16 mm (fig. 3).

longueur focale variable de	12 à 120 mm
champ objet	56° 6′
ouverture	1/2.2

Citons aussi des objectifs spéciaux comme le "Très Grand Angle" de la Société Kinoptik, qui permet d'atteindre pour le film de 16 mm un angle de champ de l'ordre de 110° avec une ouverture de $f/1.9$ et une très bonne qualité d'image (en particulier l'absence de distorsion). Sa longueur focale est $f = 5.7$ mm.

(b) Instruments Astronomiques

Nous ne parlerons pas des instruments très classiques comme la chambre de Schmidt. Le coronographe de B. Lyot, de réalisation très délicate en ce qui concerne la qualité du "poli" des surfaces optiques, est actuellement fabriqué à l'usage de divers observatoires. L'instrument le plus intéressant réalisé récemment parait être l'astrolabe de A. Danjon,[24] construit par la société O.P.L. Dans cet appareil un dispositif ingénieux de dédoublement d'image permet de maintenir en coincidence deux images d'une même étoile (image directe et image obtenue sur un bain de mercure); les erreurs mécaniques ou optiques ont été soigneusement éliminées et la précision atteint 3/100 de seconde de temps.

Mentionnons aussi des recherches sur la mise au point d'un "interféromètre corrélateur" destiné à la mesure du diamètre des étoiles en présence de scintillation atmosphérique (par Blum, Arsac, et Cagnet[25]).

(c) Microscopie

De nombreux systèmes d'observation des objets de phase ont été proposés par M. Françon ou G. Nomarski[26]; décrivons rapidement un dispositif récemment mis au point par M. Françon et Yamamoto[27] et représenté sur la figure 4.

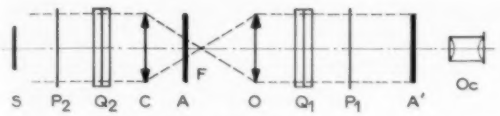


Fig. 4. Le montage de Francon-Yamamoto pour l'observation des objects de phase.

L'objectif O donne de l'objet A une image A' dédoublée par le polariscope de Savart Q_1. On peut faire interférer ces 2 images et suivant la valeur du décalage on a deux types de méthodes. Si le décalage est grand par rapport à l'objet, l'une des images interfère avec le fond uniforme de l'autre. Les images sont alors identiques à celles qui sont obtenues avec un interféromètre ordinaire. Si le décalage est petit par rapport à l'objet, on a une méthode différentielle: ce sont les variations du chemin optique qui sont décelées et non le chemin optique lui-même (strioscopie interférentielle). Pour pouvoir utiliser une source large S quelconque, il faut placer un autre polariscope de Savart Q_2 avant l'objectif C. Un polariseur P_1 placé après Q_1 et un polariseur P_1 placé avant Q_1 complètent le dispositif. La biréfringence de l'ensemble Q_1 Q_2 reste constante quelle que soit l'inclinaison des rayons et l'on peut employer une source large S tout en ayant une charge uniforme.

Citons encore le micromanipulateur de Fonbrune[28] qui permet d'exécuter des opérations très délicates à l'échelle microscopique.

(d) Instruments Divers

1. Dans le domaine de l'endoscopie médicale la contribution française est due principalement à la réalisation d'un gastroscope par l'O.P.L.[29] et aux travaux de J. Vulmière[30] sur les méthodes d'éclairage par fibre de quartz.

2. Les techniques d'imprimerie pourront bénéficier de la mise au point de machines à copier les textes dactylographiés dans lesquels une optique à lentille cylindriques permet d'ajuster la longueur de chaque ligne à la valeur convenable et de modifier éventuellement l'inclinaison des lettres.[31]

3. Dans le domaine des applications à la physique nucléaire un appareil optique destiné au dépouillement des clichés de chambres à bulles (appelé Enetra) a été mis au point par la S.O.M. et adopté par le Centre Européen de Recherches Nucléaires (Genève).

4. L'océanographie a donné lieu à la mise au point de nombreux appareils de photographie, de mesures polarimétriques, etc., en particulier sous la direction de A. Ivanoff.[32]

5. La polarimétrie de haute précisiou a fait des progrés importants grace aux travaux de J. Badoz.[33]

B. Imagerie en Ondes Longues

Nous limiterons cette étude au seul problème de l'imagerie en ondes longues, qui a été abondamment étudiée en France par l'équipe de Radioastronomie de l'Observatoire de Meudon, et par le groupe de Recherches de la Compagnie Générale de Télégraphie sans fil (C.S.F.) animée par J. C. Simon.

L'imagerie en ondes longues est actuellement utilisée en radioastronomie et dans les techniques du Radar passif. L'idée de base est le fait qu'une antenne est un instrument directif qui pour un même flux incident unité délivre une puissance $g(u,v)$ fonction de la direction d'incidence u,v des ondes électromagnétiques. Pour les antennes utilisables comme radiotélescopes, $g(u,v)$ possède un fort maximum dans une certaine direction appelée axe de l'antenne, en sorte qu'il est possible de mesurer la luminance moyenne dans un petit angle solide entourant l'axe de l'antenneK.En se limitant à ce point de vue assez empirique, les qualités d'une antenne sont: (1) la largeur à demi puissance du diagramme de rayonnement $g(u,v)$ qualité comparable au pouvoir séparateur; (2) le niveau des maximums secondaires en dehors de l'axe, qualité comparable à l'apodisation optique.

On a été amené, indépendamment des travaux maintenant célèbres on optique de Duffieux et de ses successeurs, à considérer une antenne comme un filtre de fréquences d'espace.[34,35] Résumons ici les résultats essentiels.

On limite le problème à une sule dimension, ce qui correspond au cas des antennes dont une seule des dimensions est grande devant la longuer d'onde. Etant donné que l'ensemble antenne-récepteur est linéaire en puissance et que les propriétés de directivité de l'antenne sont invariantes si l'on fait tourner celle-ci ou si, l'antenne étant fixe sur la terre l'astre se déplace devant elle par suite de la rotation de la terre, alors la puissance reçue lorsqu'un astre de répartition de luminance $f(u)$ se trouve dans une direction u′ est donnée par

$$h(u') = \int_{\text{astre}} f(u)g(u' - u)du = f * g.$$

Elle est ainsi donnée par le produit de convolution de f et g.[36] Si F,G,H sont les transformées de Fourier de f,g,h, alors $H = F.G$ et l'on retrouve ainsi la propriété de filtrage des fréquences d'espace de l'objet f par la fonction G caractéristique de l'antenne.

Une différence intéressante avec l'optique classique

vient de ce que les variables utiles sont angulaires, et les fonctions f,g,h périodiques, de période 2π. Il est alors naturel de développer ces fonctions en séries de Fourier:

$$f(u) = \Sigma F_p \exp(ipu),$$
$$g(u) = \Sigma G_p \exp(ipu),$$
$$h(u) = \Sigma F_p G_p \exp(ipu).$$

On retrouve la même propriété de filtrage des fréquences de f; la seule particularité vient de ce que les spectres sont ici des spectres de raies aulieu d'être des spectres continus.

La liaison entre spectre de g et structure de l'antenne se fait comme en optique classique à partir du principe d'Huygens. Si $b(t)$ est la répartition de courants sur l'antenne de longueur A, la longueur d'onde étant prise pour unité de longueur, le gain de l'antenne dans la direction u est

$$g(u) = |\int_0^A b(t) \exp(2\pi it \sin u)dt|^2.$$

On développe $\exp(2\pi it \sin u)$ en série de Fourier

$$\exp(2\pi it \sin u) = \Sigma J_p(2\pi t) \exp(ipu).$$

Il vient ainsi[1]:

$$G_p = \int_{-A}^{+A} [b(t) * b^*(-t)] J_p(2\pi t)dt.$$

Ce résultat diffère assez notablement dans sa forme de celui de l'optique classique où la fonction G est directement égale à $b(t) * b^*(-t)$.

Il en résulte que même pour une antenne de longueur finie, la bande passante en fréquences d'espace d'un radiotélescope n'est pas limitée. Comme le pouvoir séparateur d'un instrument est déterminé par la fréquence de coupure de sa fonction de filtrage, il en résulte qu'il ne devrait pas y avoir ici de problème de pouvoir séparateur. En fait il n'en est rien, car on peut montrer que si les harmoniques supérieurs ne s'annulent pas identiquement à partir d'un certain rang, ils restent néanmoins très faibles et en pratique indiscernables, ce qui rétablit une fréquence de coupure dans le spectre. La seule façon de tirer parti de cette situation consiste à s'arranger pour réduire l'importance des harmoniques pour les faibles fréquences, ce qui rehausse l'importance relative des harmoniques lointains: on obtient ainsi des antennes superdirectives.[37]

Lorsque les antennes sont suffisamment directives, on peut montrer alors que l'on retrouve la situation classique de l'optique, la fonction de filtrage étant l'autocorrélation de la répartition de courants sur l'antenne:

$$G(t) = b(t) * b^*(-t).$$

On a étudié en détail le cas des réseaux d'antennes pour lesquels la réparitition de courant est nulle partout sauf en quelques points. Alors la fonction de filtrage est de nouveau discrète, et ceci n'est utilisable que pour les objets qui peuvent être déterminés par des points discrets sur leur spectre, c'est à dire des astres dont le diamètre apparent est suffisamment petit. (Conséquence du théorème d'échantillonage). On a pu monter dans ce cas que le réseau uniforme, formé d'antennes identiques régulièrement réparties fournissait une certaine redondance de l'information et que des réseaux incomplets, déduits du précédent par suppression de certaines antennes pouvaient fournir une fonction de filtrage acceptable, voir même meilleure.[34] Ainsi le réseau formé d'antennes identiques à des abscisses qui sont entre elles comme les nombres 0, 1, 4, 6 transmet l'harmonique de rang 0 avec l'amplitude 4, et les 6 suivants avec l'amplitude 1, en sorte qu'à part un fond continu qui se superpose à l'objet, il fournit l'écart quadratique moyen minimum entre objet et image. On a montré, dupuis la réalisation de ce réseau en 1955, ce que ceci pouvait avoir de défectueux.[36]

En liaison directe avec ces conceptions, il apparait essentiel de pouvoir résoudre le problème suivant: étant donné une fonction de filtrage, réaliser une antenne dont elle soit effectivement fonction de filtrage. Le problème n'admet pas en général de solution, sauf si cette fonction est Transformée de Fourier d'une fonction positive. Dans ce cas, on sait former explicitement un certain nombre de solutions du problème. Mais il a paru important de pouvoir échapper à cette restriction, et c'est ce que réalise la connexion "en produit" de 2 antennes. Supposons en effet que l'on veuille faire un interféromètre avec deux antennes, on peut ajouter les signaux fournis par les deux antennes avant de les détecter (solution dite "en addition," la seule utilisée couramment en optique); mais il est aussi possible de mesurer la valeur moyenne du produit de ces signaux.[38] On démontre alors que la fonction de filtrage est la corrélation des répartitions de courant sur les deux antennes considérées comme distinctes. C'est le point essentiel: toute fonction de filtrage n'est pas nécessairement réalisable sur un instrument conventionnel, parce que toute fonction n'est pas nécessairement une fonction d'autocorrélation.

Les deux antennes en produit ayant des supports matériels distincts, la fonction de corrélation est toujours nulle pour la fréquence O: les antennes "en produit" ne transmettent pas les luminances constantes. Ceci a deux conséquences importantes:

1. On peut appercevoir un détail fin sur un fonc continu même s'il se détache très peu sur ce fond;

2. Si l'on fait une mesure interférométrique avec deux antennes identiques en produit, on obtient une répartition sinusoidale de luminance, mais non superposée à un fond continu; autrement dit les franges d'interférence sont à valeur moyenne nulle; il est possible de les détecter et de mesurer leur contraste, même si elles se dêplacent. Ceci rend possible les mesures interférométriques de diamètre apparent d'étoiles en présence de scintillations atmosphériques. Le succès de ces techniques ayant été confirmé en

ondes longues, l'équipe de radioastronomie de l'Observatoire de Meudon (E. J. Blum) collabore avec l'Institut d'Optique à la réalisation d'un interféromètre optique sur le même principe.

Cette technique ne permet pas la solution du problème de la réalisation d'une antenne de fonction de filtrage donnée dans le cas le plus général. L'utilisation de deux antennes élémentaires en produit au foyer d'un grand miroir fournit la fonction de filtrage comme corrélations de deux fonctions indépendantes, et permet donc d'envisager une solution totale du problème (Etude faite par E. J. Blum, à paraitre).

Signalons pour terminer que si nous avons insisté ici sur les points d'originalité de l'optique des ondes longues par rapport à l'optique classique, la réalisation d'antennes géantes, comme le miroir de Nançay (300 mètres de long) ramène au cas de l'optique classique, et les calculs de ce miroir ont été faits en collaboration avec A. Maréchal, (Institut d'Optique) en utilisant la fonction iconale. D'autre part les problèmes de pouvoir séparateur sont finalement les mêmes quelque soit la longueur d'onde, et ont fait l'objet d'une importante étude théorique à l'Observatoire de Meudon.[38]

C. Spectroscopie Instrumentale

On peut distinguer en spectroscopie les méthodes classiques (photographie ou enregistrement des spectres au moyen d'appareils à prismes ou à réseaux) et des méthodes relativement nouvelles (emploi des interféromètres de Michelson, de Fabry-Perot; techniques utilisant une modulation sélective des éléments spectraux).

Les premières ont atteint une certaine maturité et progressent surtout dans les régions spectrales d'accès relativement difficiles (ultraviolet lointain en particulier).

Au Laboratoire des Hautes Pressions du CNRS, l'équipe dirigée par A. Vodar et J. Romand a réalisé plusieurs spectrographes et monochromateurs pour cette région spectrale, comportant des dispositions originales.[39] D'autre part, des perfectionnements notables des sources existantes (étincelle glissante, étincelle initiée) ont été obtenus. En particulier une étincelle condensée dans le vide, dans laquelle le courant atteint une valeur de l'ordre de 50,000 A pendant 1 μs a été mise au point[40]; le spectre continu produit s'étend du visible à 80 A environ, ce qui représente une extension importante.

Nous nous occupersons plus longuement des méthodes complètement nouvelles, ou ayant subi des améliorations de principe dans les années récentes. La plupart des développements nouveaux ont été exposés par les participants au Colloque de Spectroscopie Interférentielle organisé par le Centre National de la Recherche Scientifique à Bellevue en 1957 et dont les travaux ont été publiés par le *Journal de Physique*.[41] A la suite de ce colloque un rapport d'ensemble sur la question, beaucoup plus détaillé que celui que nous pourrons donner ici, a été publié dans les "Reports on Progress in Physics" par P. Jacquinot[42] du Laboratoire Aimé Cotton, CNRS. Nous utiliserons essentiellement ces deux sources (en nous limitant naturellement aux réalisations francaises).

L'interféromètre à réflexions multiples, inventé par Fabry et Perot en 1896, est aujourd'hui utilisé en spectroscopie de deux façons différentes. Tout d'abord *l'enregistrement photographique* des anneaux d'interférence à l'infini, mis au point sur la plaque en même temps que l'image d'une source étendue permet d'étudier de petites variations de longueur d'onde (dues par exemple à un effect Doppler) d'une raie d'émission avec le point considéré de la source. Cette technique imaginée et appliquée pour la première fois par Fabry et Buisson en 1911 à la nébuleuse d'Orion (la plus brillante du ciel) a été considérablement améliorée par G. Courtès à l'Observatoire de Haute-Provence. Sa principale contribution (du point de vue instrumental) a été la mise au point d'un *réducteur focal* (ref. 41, p. 342) qui lui a permis de photographier en lumière $H\alpha$ des nébulosités dont les luminances sont de 10^3 à 10^4 fois plus faibles que celle de la nébuleuse d'Orion.

Le résultat le plus spectaculaire a été la première mise en évidence par des moyens optiques du centre de la Galaxie (connu seulement jusqu'ici par la raie 21 cm de l'hydrogène neutre). G. Courtès et P. Cruvellier ont pu détecter dans cette région une faible émission $H\alpha$ avec une vitesse radiale de -188 km/s en bon accord avec la valeur attendue d'après les mesures radioastronomiques (fig. 5).

Lorsque l'on ne cherche plus à résoudre spatialement la source, il est préférable d'utiliser l'étalon Fabry-Perot en liaison avec un récepteur: l'ensemble constitue alors un *spectromètre* Fabry-Perot. Le premier appareil de ce type a été construit par P. Jacquinot et C. Dufour[43] en 1948. Ses avantages principaux par rapport au spectrographe Fabry-Perot sont maintenant bien connus (rendement quantique, linéarité et reproductibilité très supérieurs du récepteur photoélectrique dans le visible et l'ultraviolet; extension possible à l'infrarouge au moyen des récepteurs photoconducteurs et thermiques) et de nombreux équipements semblables ont été depuis réalisés un peu partout. D'autre part P. Jacquinot a montré[44] que, comparé à un spectromètre à fentes muni d'un prisme ou d'un réseau, le spectromètre Fabry-Perot présente l'avantage d'une luminosité beaucoup plus grande pour un même pouvoir de résolution.

La théorie de l'instrument a été étudiée en détails par R. Chabbal[45] (LAC); Il a en particulier considéré l'association de plusieurs étalons Fabry-Perot et d'un

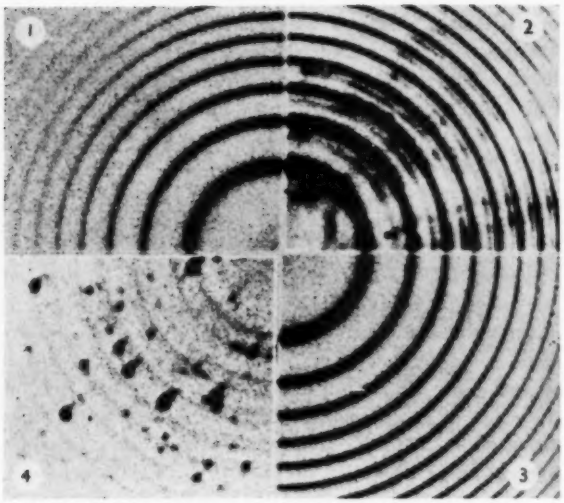


Fig. 5. Montage photographique des anneaux donnés par: une lampe à hydrogène (1 et 3); la nébuleuse M 8 (2) et la région dans la direction du centre de la Galaxie (4) (G. Courtes et P. Cruvellier).

monochromateur à fentes; l'ensemble, baptisé "spectromètre Fabry-Perot intégral" est capable d'explorer un spectre d'étendue et de complexité quelconque. Ces études ont conduit à plusieurs réalisations: un spectromètre comportant deux Fabry-Perot à exploration par variation de pression et un grand monochromateur à réseau pour l'étude à très haute résolution de structures hyperfines de raies infra-rouges; un appareil à résolution beaucoup plus faible pour le visible. Enfin le prototype d'un spectromètre Fabry-Perot transportable, pouvant fonctionner dans un environnement quelconque et plus particuliérement destiné aux dosages isotopiques par voie optique a été construit,[46] est maintenant fabriqué industriellement (fig. 6).

Les couches multidiélectriques pour étalons Fabry-Perot et filtres interférentiels ont été étudiées par P. Giacomo (LAC)[47] qui a construit un dispositif de contrôle continu de l'épaisseur pendant l'évaporation. Il a depuis étendu ses recherches à la Faculté de Caen et réalisé des couches cryolithe-iodure de plomb pour l'ultra-violet. Au Laboratoire de Recherches Physiques à la Sorbonne, R. Lennuier s'est attaqué au même problème; il a mis au point des couches iodure de rubidium-cryolithe et construit un spectromètre enregistreur à double Fabry-Perot pour l'étude en particulier de la raie 2537 A de Hg. [41](p. 319). Il a également utilisé pour cette même raie la vapeur de mercure 198 en absorption dans un champ magnétique comme filtre optique; la structure de la raie émise par une source à mercure naturelle peut ainsi être explorée comme par un spectromètre.

Dans le même laboratoire, R. Dupeyrat a construit un spectromètre Fabry-Perot enregistreur adapté à l'étude de l'effect Raman[41] (p. 351). Il a par ailleurs étudié l'emploi de cales à magneto-ou electro-striction pour réaliser un Fabry-Perot à déplacement mécanique des lames.

Une variante de l'étalon Fabry-Perot a été proposée par P. Connes (ref. 41, p. 262) (LAC) et baptisée Fabry-Perot sphérique. Son emploi dans un spectromètre photoélectrique permet un gain appréciable de luminosité dans le cas des pouvoirs de résolution extrêmement élevés; il est donc utile pour l'étude des raies très fines. Son emploi comme cavité résonante pour un LASER parait également présenter des avantages appréciables. D. A. Jackson[48] l'a appliqué avec succès à la résolution de la structure hyperfine exceptionnellement serrée de la raie de résonance du baryum observée en absorption sur un jet atomique. Il a d'autre part démontré expérimentalement qu'un accroissement considérable de l'absorption observée pouvait être obtenu en plaçant le jet à l'intérieur de l'étalon lui-même.

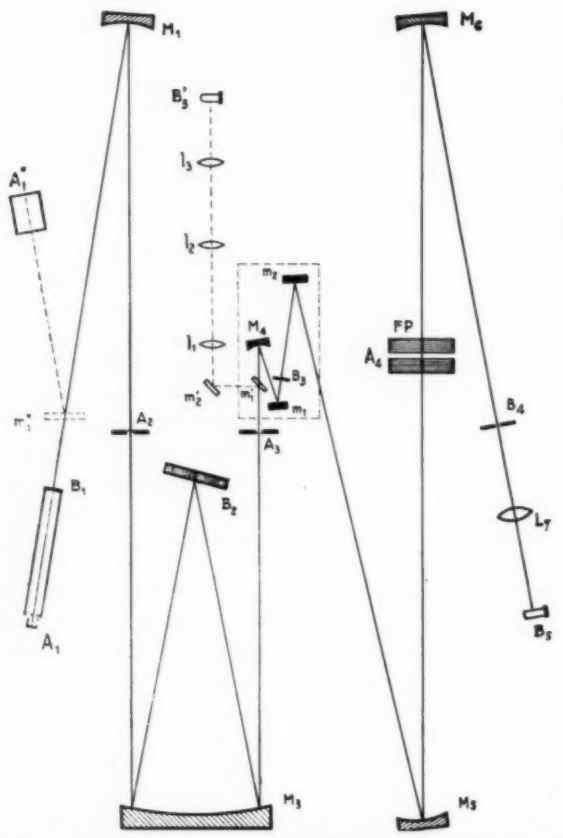


Fig. 6. Spectromètre Fabry-Perot photoélectrique "HYPEAC" (P. Jacquinot et R. Chabbal).

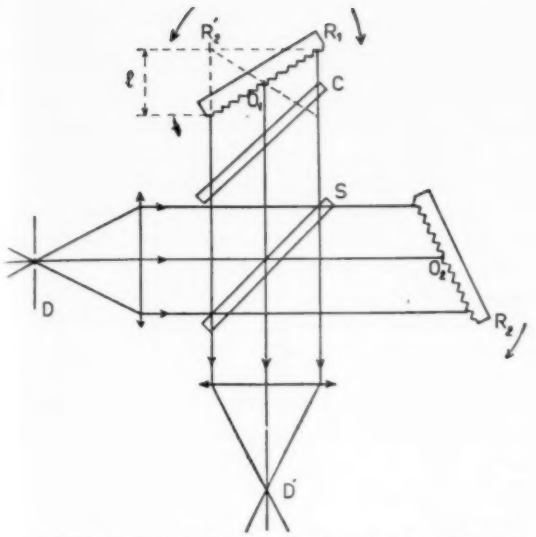


Fig. 7. SISAM: D—diaphragme d'entrée; S—séparatrice; C—compensatrice; R_1R_2—réseaux (P. Connes).

Lorsque l'on désire obtenir simultanément les structures d'un grand nombre de raies dans un spectre étendu, la plaque photographique peut donner les résultats cherchés plus rapidement que l'enregistrement photoélectrique; ce résultat était obtenu jusqu'ici en projetant les anneaux d'un Fabry-Perot sur la fente d'entrée d'un spectrographe à réseau; le principal inconvénient était la non-linéarité du spectre. Un nouveau dispositif décrit par R. Chabbal[49] élimine cette difficulté: le centre des anneaux, projeté sur la fente, est seul utilisé, et la plaque photographique se déplace dans son plan en synchronisme avec la variation de l'épaisseur optique de l'étalon, perpendiculairement à la dispersion du réseau. La luminosité du spectrographe devient en outre beaucoup plus grande parce que la dispersion le l'étalon est maximum pour des rayons quasi normaux.

Après avoir donné les différentes applications de l'étalon Fabry-Perot, nous décrirons deux méthodes qui ont récemment fait leur apparition en France et qui utilisent un principe commun: la modulation sélective d'un seul élément spectral, dont la longueur d'onde peut explorer le spectre étudié. Toutes deux tendent à procurer un gain considérable de luminosité par rapport aux spectromètres classiques à fentes.

La première décrite par P. Connes[50] utilise un interféromètre de Michelson dont les deux miroirs sont remplacés par des systèmes dispersifs identiques, par exemple des réseaux (fig. 7); il est équivalent à un interféromètre ordinaire, mais qui ne serait réglé que pour une seule longueur d'onde λ_0. En faisant varier la différence de marche entre les deux faisceaux (par exemple par rotation de la lame compensatrice) on module dans un spectre complexe le seul élément spectral de longueur d'onde λ_0. L'appareil a été baptisé Sisam (initiales françaises de Spectromètre Interférentiel à sélection par l'amplitude de modulation).

Le pouvoir de résolution du dispositif est égal au pouvoir de résolution théorique R_0 du réseau utilisé; d'autre part, l'angle solide du faisceau admissible est le *même* que celui qui serait accepté par un étalon Fabry-Perot de même R_0, donc beaucoup *plus grand* que celui du spectromètre à fentes équivalent. Une variante, l'interféromètre compensé, utilise des prismes placés contre les réseaux; l'angle solide utilisable est alors encore accru considérablement.

Le second dispositif, du à A. Girard[51] (de l'Office National d'Etudes et Recherches Aéronautiques) est le spectromètre à grille. Il dérive d'un spectromètre classique par simple remplacement des fentes d'entrée et de sortie par des *grilles linéaires* de lois identiques.

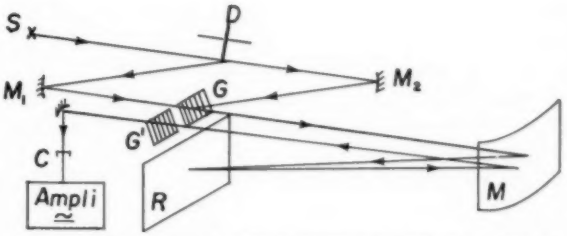


Fig. 8. Spectromètre à grille: S—source, D—disque modulateur; M—miroir collimateur; R—réseau; C—récepteur; G—grille d'entrée; G'—grille de sortie (A. Girard).

La grille de sortie est constituée de fentes alternativement *opaques* et *transparentes*, et la grille d'entrée de fentes *réfléchissantes* et *transparentes* qui sont alternativement éclairées par la source (fig. 8). Lorsque l'appareil est éclairé par une raie monochromatique et réglé pour cette raie, il y a coïncidence entre parties transparentes de la grille de sortie et image des parties transparentes de la grille d'entrée; le flux tombant sur le détecteur est alternativement nul et maximum. D'autre part, la loi de transmission des grilles est choisie telle que pour une radiation voisine (pour laquelle l'image de la grille d'entrée est décalée) les flux transmis et réfléchi soient presque égaux. La loi de répartition des pleins et des vides qui donne le plus simplement ce résultat est analogue à celle des anneaux de Newton: en négligeant la diffraction on peut montrer que le pouvoir de résolution est le même que si la fente *la plus fine* était seule utilisée, tandis que le flux lumineux disponible est la moitié de celui qui serait accepté par une fente unique de largeur égale à la *totalité* de la grille d'entrée; il est comparable à celui du Sisam compensé décrit plus haut. Dans un

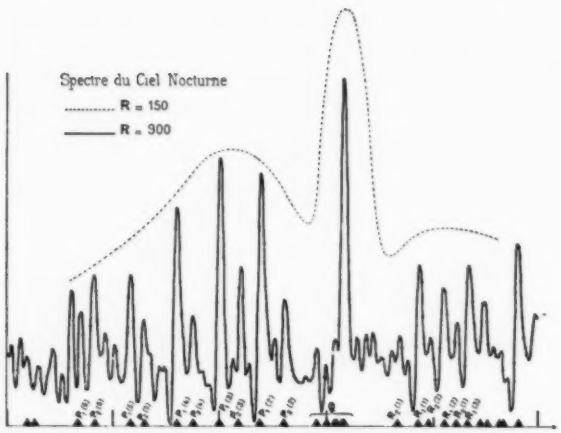


Fig. 9. Spectre d'émission du ciel nocturne: en pointillé—meilleur spectre obtenu avec un spectromètre à réseau; en traits pleins—spectre calculé à partir d'un interférogramme (J. Connes et H. Gush).

prochain numéro d'*Applied Optics*, A. Girard décrira lui-même les développements les plus récents de son appareil.

Il nous reste à parler d'une méthode récente mais pourtant déjà bien connue par le succès qu'elle remporte un peu partout dans le monde: la Spectroscopie par transformation de Fourier. Bien qu'on puisse la faire remonter aux travaux de Rubens et Wood (1911), ses propriétés remarquables et ses avantages n'ont été établis que récemment, de façon indépendante, par P. Fellgett en Grande-Bretagne et P. Jacquinot[52] en France. Il est à peine nécessaire d'en rappeler le principe (on enregistre au moyen d'un interféromètre à deux ondes à différence de marche variable un interférogramme qui est la transformée de Fourier du spectre; celui-ci s'obtient par le calcul a posteriori de la transformée de Fourier de l'interférogramme) ou les avantages (aucune dispersion n'étant nécessaire, l'énergie de tous les éléments spectraux étudiés est reçue simultanément et intégrée pendant toute la durée de l'enregistrement).

Une étude théorique de cette méthode a été faite par J. Connes[53] qui a particulièrement envisagé la question du calcul numérique des transformées de Fourier et du rapport signal sur bruit dans l'interférogramme et dans le spectre. Deux applications expérimentales ont été faites, toutes deux dans l'infrarouge proche: une étude du spectre d'émission du ciel nocturne (fig. 9) et une autre du spectre de recombinaison du germanium et de son effet Zeeman dans le champ magnétique du grand électroaimant de Bellevue.

D'autre part la méthode de Michelson qui utilise seulement la *visibilité* des franges (et non l'interférogramme complet) n'est pas abandonnée. Elle a, au contraire, été portée à un grand degré de perfection au Bureau International des Poids et Mesures à Sevres par J. Terrien (ref. 41, p. 390)[54] qui a mis au point une méthode de mesure par enregistrement photoélectrique, à la fois de la visibilité et de l'excédent fractionnaire de l'ordre d'interférence; les mesures de la visibilité V sont exploitées par le tracé de la courbe $\log V/D$ en fonction de la différence de marche D qui permet de séparer immédiatement les causes d'élargissement de la raie (par exemple dans le cas d'un profil dû à la combinaison d'une forme Doppler et d'une forme de résonance fig. 10). Enfin la discussion des différentes causes d'erreur dans la mesure de l'excédent fractionnaire lui a permis d'atteindre, dans les meilleures conditions, sur la raie orangée du krypton, une erreur de pointé de l'ordre du millième de frange avec un ordre d'interférence égal à 10^6 ce qui laisse espérer une précision de l'order de 10^9 dans la définition de sa longueur d'onde. Ses travaux ont fortement contribué à faire adopter cette raie comme nouvel étalon international de longueur.

D. Spectroscopie Atomique

Il y a peu de centres où la spectroscopie atomique soit étudiée pour elle-même. Le plus important est le laboratoire Aimé Cotton dirigé par P. Jacquinot où une douzaine de chercheurs se consacrent à la spectroscopie atomique en utilisant les nouvelles méthodes instrumentales mises au point dans ce laboratoire. Ce sont surtout les études à haute résolution qui y sont développées, mais une assez large application en est faite à l'analyse des termes des spectres complexes; ce même type d'étude est en voie d'extension à l'infrarouge proche. Dans d'autres centres (Universités de Paris, de Caen, de Lille, de Rennes, de Dakar, Laboratoire des Hautes Pressions du CNRS, Commissariat

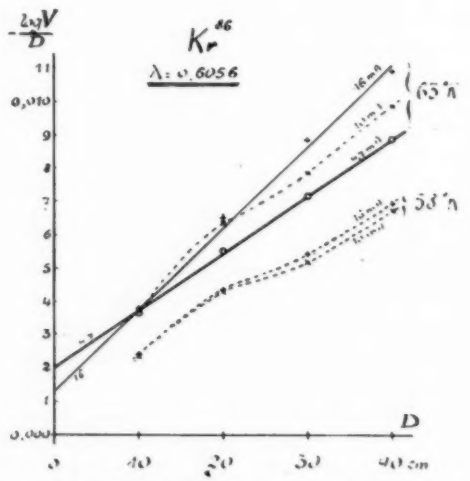


Fig. 10. Graphique — log V/D en fonction de D pour la raie $\lambda = 0.6056\ \mu$ de Kr^{86} pour différents courants et températures (J. Terrien).

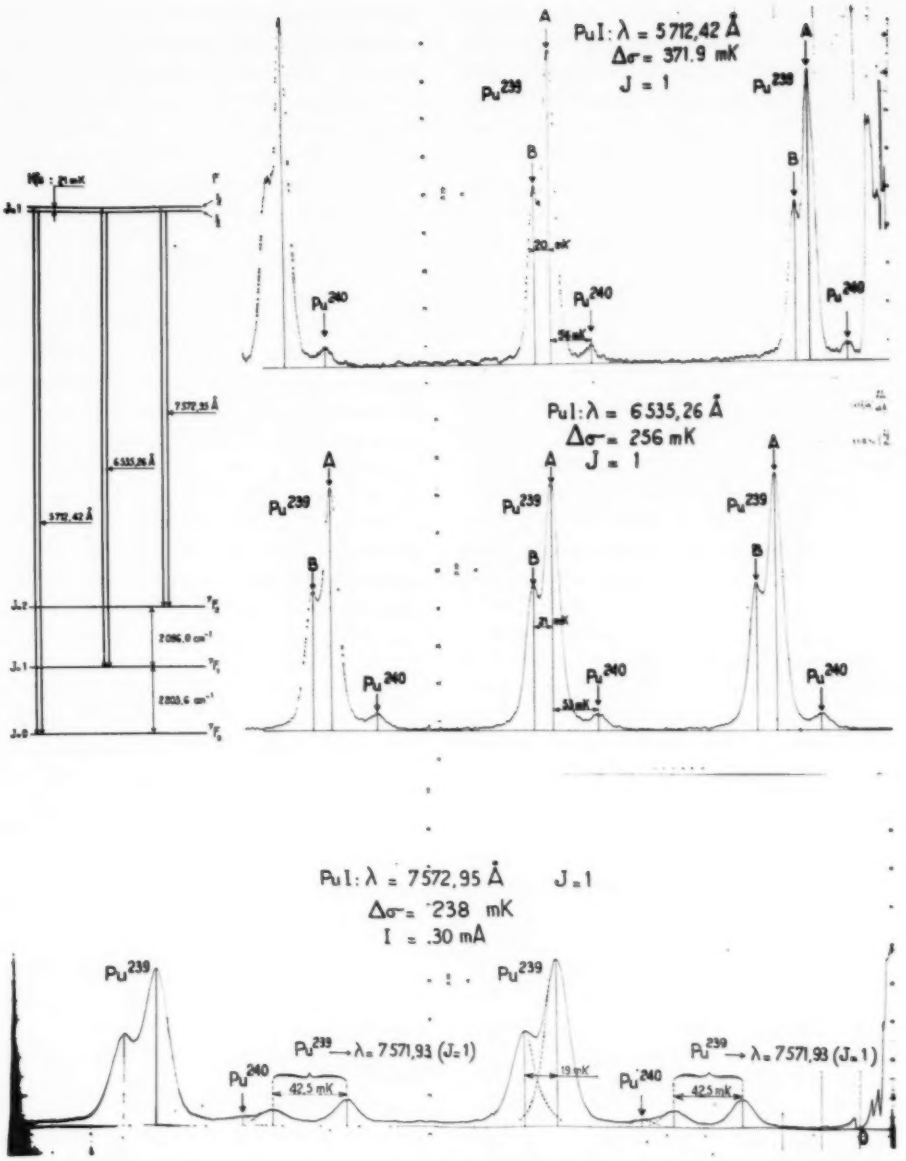


Fig. 11. Exemple d'application de la spectroscopie a haute resolution a la classification. La structure hyperfine et l'effet isotopique identiques pour ces trois raies montrent qu'elles ont un niveau commun avec $J = 1$ et permet d'interpréter l'ensemble comme étant le triplet $^7F_{0,1,2} - 17{,}500.88_1$. La structure des 3 premiers niveaux du multiplet fondamental $^7F_{0-6}$ du spectre du Pu I est ainsi définitivement établie.

à l'Energie Atomique, Observatoires), l'intérêt se porte surtout sur les effets divers subis par les raies et les niveaux, ou sur les conditions de vie ou de transfert des niveaux, ainsi que sur les applications de ces effets.

Structure Hyperfine et Déplacements Isotopiques

Dans le domaine de la structure hyperfine, les problèmes nécessitant la plus haute résolution ont été traités par D. A. Jackson (Laboratoire Aimé Cotton), grâce à sa technique bien connue des jets atomiques. Les raies de résonance du Gallium ont permis de mesurer le rapport des moments nucléaires magnétiques des isotopes 69 et 71. Dans le cas de l'Indium un résultat remarquable est une étude complète de l'effet Zeeman hyperfin[55] qui n'a été possible que grace à l'emploi d'un étalon Fabry-Perot double. L'emploi d'un jet

atomique placé à l'intérieur d'un Fabry-Perot sphérique a permis de résoudre la structure isotopique de la raie de résonance du Barium[56] (de l'ordre de 2 mK) qu'aucun expérimentateur n'avait pu résoudre jusqu'alors.

De nombreuses études de structures hyperfines ont été faites en émission avec, le plus souvent, des lampes à cathode creuse refroidies à l'azote, à l'hydrogène, ou même à l'hélium liquides. De nouveaux problèmes ont été abordés d'anciens problèmes ont été repris dans de meilleures conditions, grâce au dévelopment du spectromètre Fabry-Perot photoélectrique qui permet de mesurer les écarts et les intensités avec plus d'exactitude et de sécurité. Les études ont porté sur: Li; Pd, Cd, In I et In II, Nd I et Nd II, Lu, W, Os, Pb, U, Pu; le mercure lui-même, étudié dans presque tous les laboratories de structure hyperfine n'a pas échappé aux investigations de plusieurs laboratories français qui en ont étendu l'étude en améliorant la précision. Toutes ces études ont conduit à des déterminations de spins, de moments nucléaires magnétiques et quadrupolaires électriques, et de déplacements isotopiques. Ces travaux ont été faits au Laboratoire Aimé Cotton principalement par Jackson, Blaise,[57] Chantrel, Gerstenkorn, Tomkins, et au Laboratoire des Recherches Physiques de la Sorbonne, par Lennuier. Les résultats les plus intéressants sont relatifs à l'Uranium 235,[57] et au Lutécium 176,[58] pour lesquels existait un doute même sur le spin nucléaire, et au Plutonium 239 dont le moment magnétique était très douteux.[59]

Le problème particulier de la structure hyperfine de ^{3}He, qui est du même ordre de grandeur que sa structure fine, a été traité au Laboratoire Aimé Cotton. Dans cette expérience la source était refroidie à l'hélium liquide et la largeur des raies mesurées montrait que la température était inférieure à 6°K.[60] La structure fine de ^{4}He, dont l'intérêt théorique est évident, a été étudiée en même temps, avec une précision considérablement accrue par rapport aux résultats antérieurs.[61]

Classification des Spectres (Term Analysis)

En plus de leur application à la détermination des propriétés nucléaires, les mêmes études à haute résolution ont été appliquées de façon extensive à la classification d'un certain nombre de spectres. La structure hyperfine permet en effet de déterminer les valeurs du nombre quantique J qui peuvent, par exemple, échapper à l'effet Zeeman; le déplacement isotopique permet de grouper les raies en familles, mettant en jeu les mêmes configurations électroniques. Un gros effort a été fait sur le spectre de l'Uranium; grace au déplacement isotopique 235–238, J. Blaise a pu confirmer une partie de la classification antérieure, l'infirmer dans quelques cas, et accroître considérablement le nombre de niveaux et de raies classées. Dans le cas du Plutonium, où même la configuration fondamentale n'était pas connue avec certitude, S. Gerstenkorn[62] en utilisant essentiellement les mesures d'intensité dans les multiplets hyperfins (voir un exemple sur la fig. 9), a pu déterminer la configuration et le multiplet fondamental ainsi que les valeurs de J d'un certain nombre de niveaux. Des travaux du même gente ont été poursuivis sur le tungstène et l'osmium.

Perturbations Diverses

Les perturbations diverses des raies, et notamment les effets de pression, ont été étudiées dans un domaine de pression très étendu. R. Lennuier[63] a pu mettre en évident une dissymétrie sur la raie de résonance de Hg à partir de pressions aussi faibles que 0.05 mm. Il utilise pour cela l'absorption d'une raie exploratrice de 5 mK de large découpée dans une raie d'émission par un étalon Fabry-Perot triple à balayage par pression. L. Herman a étudié l'élargissement et le déplacement des raies de divers éléments par l'effet Stark interionique, notamment en comparant dans un même plasma les raies de l'hydrogène et des raies métalliques. Au Laboratoire des Hautes Pressions du C.N.R.S., S. et J. Robin ont étudié les perturbations apportées aux raies de résonance des alcalins, du Thallium et du Mercure, par de fortes pressions de gaz rares (jusqu'à 6000 atmosphères).[64] Les effets (apparitions de bandes satellites, déplacements, élargissements) qui sont parfois considérables posent des problèmes théoriques importants et sont susceptibles de donner des renseignements utiles sur les fluides denses.

Les effets des chocs de première et de deuxième espèces sur les atomes de mercure placés sur le niveau de résonance par excitation optique ont été étudiés par J. Cojan à Caen. En particulier le choc

$$\mathrm{Hg}\,(^3P_1) + \mathrm{N_2} \rightarrow \mathrm{Hg}\,(^3P_0) + (\mathrm{N_2} + \text{vibrations})$$

permet d'atteindre le niveau métastable $^3P_0$, permet d'observer l'émission de la raie interdite $^3P_0$–$^3s_0$ (isotope impair seulement) et intervient dans une méthode de séparation isotopique photochimique.[65]

Applications

Nous ne parlerons pas ici de l'utilisation courante de la spectroscopie atomique à l'analyse chimique qui sort du cadre de cet exposé: nous signalerons seulement l'existence d'un groupement très actif, le Groupement pour l'Avancement des Méthodes Spectrographiques (G. A. M. S.), rassemblant des ingénieurs et des scientifiques. L'étude de l'utilisation de l'ultraviolet lointain (autour de 1000 A) pour le dosage de certains métalloides a été entreprise par G. Ballofet[66] et a donné des résultats prometteurs: les raies intéressantes semblent être les raies de résonance des ions alcalinoides (par exemple C IV, P V, S VI).

L'analyse isotopique a été étudiée depuis plus de

cinq ans au Laboratoire Aimé Cotton sur divers cas, Li, Pb, Hg, U, Pu. Dans certains cas la méthode est compétitve avec la spectrométrie de masse.[67]

Les mesures de températures ont été abordées en divers endroits, mais peu de résultats ont été publiés; au C.E.A., Breton et Herman[68] ont mesuré la température ionique dans le plasma d'hydrogène dans une décharge toroïdale en utilisant l'effet Doppler des raies de C III, ainsi que des températures électroniques. Dans le même ordre d'idées, l'effet Stark a été utilisé par L. Herman et par J. Brochard[69] pour des mesures de densité ionique et de champ.

L'étude interféromètrique de la largeur Doppler de la raie verte de l'oxygène émise par le ciel nocturne a permis à Perrin de mesurer la température des atomes émetteurs, et par conséquent l'altitude de la zone émettrice.

Travaux purement theoriques

L'examen de ce genre de travaux nous éloignerait trop du domaine de l'optique. Outre le travail fondamental de J. P. Barrat (cf. section G) nous citerons seulement quelques travaux relatifs à l'atome d'hélium. Pour faciliter l'étude des problèmes pratiques Ph. Pluvinage et ses collaborateurs se sont attachés à donner une représentation approchée des fonctions d'onde ne comportant qu'un petit nombre de termes. H. Chantrel[70] a fait une étude complète du mélange de la structure fine et de la structure hyperfine de l'hélium 3, et Descomps a étendu cette étude en y incluant l'effet Zeeman.

E. Spectres des Solides

La spectroscopie, dont le développement a été d'une importance capitale pour la connaissance des atomes et des molécules, commence seulement à se développer en ce qui concerne l'étude du corps solide. Mais on peut espérer beaucoup de ce domaine de recherche qui est en plain essor, comme toute la physique du corps solide.

Si l'on en excepte l'étude des cristaux moléculaires, qui se rattache directement à l'étude des molécules, et l'étude des spectres de vibration, qui seront traités ailleurs, on peut diviser les recherches éffectuées en deux parties.

Dans l'une, on étudie les spectres de transition électronique d'ions paramagnétiques perturbés par le champ cristallin immédiatement voisin.

Dans l'autre, les transitions électroniques se font entre les états relatifs à l'ensemble du cristal; les semi-conducteurs sont principalement étudiés et les impuretés chimiques ou physiques peuvent alors jouer un grand rôle.

Les difficultés techniques sont assez grandes: obtention et taille de monocristaux, parfois en lames très minces, nécessité de basses températures pour diminuer l'energie d'agitation thermique du réseau.

L'étude des spectres d'absorption d'ions paramagnétiques perturbés par le réseau cristallin est poursuivie par L. Couture et ses collaborateurs au laboratoire Aimé Cotton à Bellevue.

Les ions particulièrement étudiés sont des ions de la série du fer: Cr^{3+}, Mn^{2+}, Co^{2+}. Les spectres d'absorption de monocristaux orientés sont faits à différentes températures, jusqu'à 2°K, et avec des champs magnétiques atteignant 40 koe.

Les spectres des ions paramagnétiques se révèlent comme un moyen très sensible d'étude des variations du champ cristallin; ils ont permis la découverte d'un changement de phase du premier ordre à 60°K dans l'alun de chrome et de potassium; ils montrent l'influence de la concentration en ions paramagnétiques dans la stabilité des diverses phases cristallines d'une même substance, et l'importance du passé du cristal sur son état.[71]

L'effet Zeeman[72] des niveaux déjà séparés par le champ cristallin, permet de connaître le facteur spectroscopique g aussi bien pour les niveaux excités que pour le niveau de base, qui peut être étudié, d'autre part, en résonance paramagnétique.

S. Nikitine et ses collaborateurs, à la Faculté des Sciences de Strasbourg, étudient les spectres de substances spectroscopiquement pures: cuprite (Cu_2O), halogénures de cuivre et de thallium, iodures d'argent, de mercure et de plomb. Des spectres d'absorption de lames minces, ainsi que des spectres de réflexion et de fluorescence, sont obtenus à température ordinaire et à basse température.

Des travaux théoriques récents, faits à l'étranger, sur les spectres de l'exciton ajoutent à l'interêt de ces reèherches; ils permettent le classement et l'interprétation des spectres, suscitent des recherches nouvelles, telles que des mesures quantitatives de l'intensité des raies d'absorption.[73,74]

Au laboratoire de luminescence de la Faculté des Sciences de Paris, un groupe important de chercheurs comprenant M. Curie, G. Destriau, D. Curie, J. Mattler et E. Grillot a fait de nombreuses études sur la luminescence des solides. Des études particulières permettent une confrontation entre théorie et expérience: étude du déclin de la luminescence, de la thermoluminescence, c'est à dire de la variation de l'intensité de luminescence en fonction de la température, les substances étant excitées à basse température, action d'un champ électrique statique ou sinusoidal. La luminescence de certains compteurs excités par rayons X ou γ ou par particules α, et son renforcement par le champ électrique sont aussi étudies.[75,76]

E. Grillot et ses collaborateurs partent d'un point de vue plus chimique et mettent au point des méthodes de préparation de substances purifiées électrochimiquement et controlées par microdosage d'isotopes radio-

actifs.[77] La préparation, par synthèse en phase gazeuse, de gros monocristaux de CdS activés par du cuivre ou de l'argent permet l'étude de la fluorescence infrarouge de ces cristaux.

La fluorescence classique verte étant liée à des lacunes du réseau, E. Grillot et ses collaborateurs la réduisent en en préparant des cristaux par sublimation, à température aussi faible que possible, de façon à opérer avec de la vapeur dissociée. Ils découvrent alors une série de fines raies bleues dans laquelle certains maximums obéissent à une loi de série quasi-hydrogénoïde. Ces recherches sont compléttées, en collaboration avec E. F. Gross, par l'étude du spectre d'absorption et de l'effet Zeeman.[78]

D'autres équipes, bien que n'étant pas spécialement spectroscopistes, voient leur interêt croître dans ce domaine de recherche. Telle est l'équipe de M. Balkanski à l'Ecole Normale Supérieure de Paris qui étudie les semi-conducteurs. M. Balkanski et ses collaborateurs observent que des transferts d'énergie dans les solides se font par l'intermédiaire d'excitons dans des monocristaux, par exemple le sulfure de cadmium CdS, aussi parfaits que possible. Ils sont conduits à étudier théoriquement toutes les transitions optiques permises dans les cristaux du type wurtzite, transitions entre bandes, transitions dues à l'exciton ou aux vibrations du réseau.[79] Des études expérimentales sont faites sur la würtzite CdS, le rutile TiO_2, ou le silicium contenant des atomes de carbone en impuretés.[80]

F. Spectroscopie Moleculaire

Les recherches que nous serons amenés à envisager sous ce titre général sont de trois types:

(a) En toute rigueur, les spectres des molécules doivent être obtenus en travaillant sur des molécules à l'etat libre, c'est à dire sur des gaz à faible pression. Lorsque ces conditions experimentales sont difficiles à realiser, on utilise eventuellement, avec une précision moindre, des spectres de substances à l'etat liquide ou solide en négligeant les intereactions entre la molécule étudiée et les molécules voisines.

(b) Dans un autre type d'études on ne néglige plus ces interactions mais on étudie au contraire la façon dont le spectre de la molécule libre est modifiée par l'environnement dont l'effet se traduit par une perturbation relativement faible.

(c) Des actions intermoléculaires fortes peuvent être étudiées sur les gaz comprimés ou sur des systèmes à l'état liquide ou solide. Dans ces études on ne peut plus considerer des molécules isolées. Des complexes faisant intervenir plusieurs molécules jouent alors un rôle très important.

A la spectroscopie moléculaire se rattache le cas des radicaux libres à durée de vie plus ou moins longue qui peuvent être étudiés soit à l'état gazeux soit piégés dans des matrices à basse température.

Nous envisagerons les différents types d'études que nous venons de décrire en considérant successivement les spectres électroniques et les spectres de vibration ou de vibration-rotation.

Les techniques instrumentales utilisées par les expérimentateurs sont le plus souvent classiques. Nous renvoyons au chapitre consacré à la spectroscopie instrumentale pour une description des techniques spéciales conduisant à des dispositifs à très haute résolution ou à très haute luminosité ou permettant de résoudre des problèmes particuliers posés par l'étude des régions extrêmes du spectre (ultraviolet lointain et infrarouge lointain). Par ailleurs l'étude des spectres moléculaires a suscité de nombreuses recherches instrumentales liées aux conditions physiques imposées à la substance étudiée (hautes pressions, basses températures, radicaux libres, ions obtenus par l'action d'un faisceau d'électrons sur un jet moléculaire etc....). Des techniques instrumentales particulières ont également été mises au point pour suivre l'évolution d'un phénomène dans le temps ce qui permet en particulier d'étudier la cinétique des réactions chimiques.

I. Spectres Electroniques

Les transitions spectrales impliquant un changement de l'état électronique peuvent être observées soit en émission ou en absorption (généralement dans le visible ou l'ultraviolet, éventuellement dans l'infrarouge), soit en fluorescence ou en phosphorescence.

(a) Spectres des Molecules et des Radicaux Libres à l'État Gazeux

Spectra d'Emission

Les spectres d'émission de diverses molécules diatomiques ont été étudiés à Lille par J. Roig, et ses collaborateurs. Citons en particulier l'analyse des spectres visible ou ultraviolet des molécules Ag_2, Cu_2, Au, AuCu, AgAu, AgCu, AuMg, AlAu par J. Ruamps[81] qui poursuit mintenant ses recherches à Bordeaux. Les molécules AuCa, AuBa, AuSr, AuMg et MnS ont également été étudiées, principalement par J. Schiltz.[82] Ces divers spectres ont été obtenus en utilisant comme source un four de King dont le corps est un tube de graphite.

Parmi les travaux effectués à Lyon par J. Janin et ses collaborateurs nous citerons des recherches spectroscopiques sur l'émission des flammes: en particulier une étude de la flamme méthane-ammoniac-oxygène dans laquelle ils ont observé l'émission de la molécule CN et des radicaux CH, NH, NH_2 et OH.[83]

Les recherches de L. et R. Herman et S. Weniger portent principalement sur les spectres de molécules qui présentent un intérêt pour l'astrophysique et la

physique de la haute atmosphère. Ils ont analysé les spectres d'émission de O_2, O_2^+, N_2, N_2^+, OH, OH^+ et OD obtenus soit au laboratoire, soit dans les aurores polaires, soit dans les comètes.[84] Toujours dans le domaine de l'astrophysique citons les études effectuées sur la photosphère et les taches solaires par G. Laborde qui a étudié plus particulièrement les molécules MgH, CH, CN, NH et OH pour en déduire des températures de rotation.[85]

S. Leach et ses collaborateurs ont analysé les spectres d'émission des benzènes monosubstitués. Ils ont établi une corrélation entre la nature du substituant et la structure vibrationnelle de la première transition électronique singulet-singulet.[86] Ils ont par ailleurs construit un appareil permettant l'étude spectroscopique d'un jet moléculaire sous l'action d'un faisceau d'électrons d'énergie comprise entre 10 et 1000 ev. Cet appareil s'est révélé une source spectrale de grande pureté. Les expériences ont porté sur les transitions électroniques de CO_2^+ et N_2O^+.[87]

Spectres d'Absorption

Les études les plus importantes ont été effectuées par B. Vodar, J. Romand et leurs collaborateurs dans le domaine de l'ultraviolet lointain, elles portent notamment sur les molécules suivantes: ClH, BrH, IH, FH, NO, N_2O, H_2O, D_2O, N_2, CH_3OH, CO_2 ainsi que les halogénures d'alcoyle. Ces spectres d'absorption mettent en évidence, par des discontinuités d'absorption, la présence des potentiels d'ionisation des molécules. Par ailleurs les mesures faites sur certaines bandes continues permettent de préciser la courbe d'énergie potentielle de l'état excité.[88]

Dans le même laboratoire toute une sêrie d'études a été effectuée dans l'ultraviolet et dans le visible sous des pressions élevées pouvant atteindre 6.000 atmosphéres. L'étude du déplacement et de la déformation des raies spectrales permet d'obtenir des renseignements sur les forces intermoléculaires.[89]

(b) Spectres d'Absorption, de Fluorescence ou de Phosphorescence des Liquides et des Solides

De nombreuses études ont été effectuées à Bordeaux par A. Rousset et ses collaborateurs; citons en particulier les travaux sur l'absorption des dérivés méso-anthracéniques[90] et des paraquinones polynucléaires[91] sur l'absorption des colorants à l'état triplet en milieu vitreux à 77°K,[92] sur la fluorescence des amino-acides en solution aqueuse[93] et des colorants en solution solide dans le plexiglass,[94] sur les transferts d'activation dans les cristaux moléculaires dopés (c'est le solvant qui absorbe et l'impureté qui émet le rayonnement de fluorescence, mais cette émission est retardée).[95]

S. Leach et ses collaborateurs ont étudié à 77°K les spectres d'absorption, de fluorescence et de phosphorescence du benzène à l'état vitreux. L'apparition de bandes interdites pour la symétrie D_{6h} montre que cette symétrie est modifiée par la perturbation due au solvant.[96] Ils ont également étudié les spectres de fluorescence dans le visible des radicaux benzyle piégés pour lesquels l'effet isotopique correspondant au remplacement de *H* par *D* a été analysé en détail.[97]

Le spectre d'absorption dans l'ultraviolet lointain du benzène piégé dans des matrices à basses températures a été étudié par B. Vodar, J. Romand et leurs collaborateurs qui ont montré que les perturbations des bandes peuvent être rattachées à l'indice de refraction de la matrice.[98]

Les spectres d'absorption, de fluorescence et de phosphorescence de substances aromatiques pures ou en solution dans le pentane ont été étudiés à Marseille par P. Pesteil.

II. Spectres de Vibration et de Vibration-Rotation

Nous considèrerons successivement les spectres d'absorption infrarouge et les spectres de diffusion Raman, en réservant pour un troisième paragraphe le cas des cristaux. Nous dirons enfin quelques mots sur les mesures d'indices de réfraction.

(a) Spectres d'Absorption Infrarouge

La spectroscopie dans l'infrarouge a débuté en France avec les premiers travaux de J. Lecomte. Elle a surtout donné lieu à des recherches effectuées sur des transitions de vibration obtenues à résolution faible ou moyenne. De telles études ont de nombreuses applications chimiques (détermination des structures moléculaires) ou physiques (détermination des vibrations normales des molécules et des cristaux; étude des forces intermoléculaires).

Cependant plusieurs laboratoires sont en train de s'équiper en spectrographes à haute résolution, ce qui laisse prévoir le développement de recherches plus nombreuses sur la structure rotationelle des bandes de vibration-rotation des molécules à l'état gazeux.

Il importe de souligner les travaux effectés à Nancy par A. Hadni et ses collaborateurs dans le domaine de l'infrarouge lointain. Ils ont construit des spectrographes leur permettant de couvrir le domaine de longueurs d'onde compris entre 50 μ et 2500 μ.[99]

Determination des Vibrations Normales et des Structures Moléculaires

D'innombrables travaux ont été effectués sur l'utilisation des spectres d'absorption infrarouge pour déterminer les vibrations normales des molécules ou préciser leur structure. Les principaux laboratoires ayant travaillé sur ces problèmes sont ceux de J. Lecomte, P. Barchewitz, A. Hadni, J. P. Mathieu, M. L. Josien, J. Chedin, F. Mathis, R. Romanet.[100]

Etude de Action Intermoléculaires

De nombreuses recherches ont été effectuées dans les mêmes laboratoires, plus particulièrement dans celui de M. L. Josien,[101] sur les modifications des spectres de vibration dues à l'action des molécules voisines (influence des solvants, liaison hydrogène).

Une étude particulièrement complète des actions intermoléculaires est poursuivie par B. Vodar et ses collaborateurs. Des travaux sur les gaz effectués jusqu'à des pressions très élevées permettent de suivre les variations du profil d'une bande de vibration-rotation en fonction de la densité et de la nature des molécules perturbatrices.[102] Ces recherches ont donné lieu à des travaux théoriques sur le mécanisme des interactions moléculaires.[103]

Application de la Spectroscopie Infrarouge à la Physique de l'Atmosphere

Utilisant des spectres obtenus sur les instruments construits par M. Migeotte, E. Vigroux a entrepris une étude approfondie de l'ozone atmosphérique dont il a, en particulier, déterminé la distribution verticale.[104] Ses résultats ont pu être vérifiés par des mesures directes à l'aide de radiosondages effectués au même instant et au même lieu que les observations spectroscopiques. Ces recherches sont appelées à se développer grâce à la station d'observation que M. Migeotte et E. Vigroux sont en train d'installer dans le domaine du Four solaire à Montlouis.

(b) Spectres de Diffusion Raman

C'est à J. Cabannes que revient le mérite d'avoir fondé l'école française de spectroscopie Raman. De nombreuses recherches ont été effectuées dans ce domaine par ses élèves, notamment au Laboratoire des Recherches Physiques de la Sorbonne.

J. P. Mathieu et ses collaborateurs ont principalement travaillé sur les cristaux, nous reviendrons sur leurs résultats dans le prochain paragraphe.

R. Dupeyrat a étudié en fonction de la température la variation de la structure isotopique de la bande Raman de vibration ν_1 de la molécule $SiCl_4$.[105]

R. Lennuier a considéré le case où la raie excitatrice a une fréquence voisine d'une fréquence propre, c'est à dire le cas intermédiaire entre la diffusion Raman et la résonance.[106]

A Lille, M. L. Delwaulle et ses collaborateurs ont principalement étudié les échanges d'halogènes pour des halogénures de bore, de phosphore, d'arsenic ou d'étain. Une étude d'ensemble de l'évolution des spectres Raman a été faite dans le cas des molécules pyramidales et planes (AX_3, AX_2Y, AXY_2, AY_3) et dans le cas des molécules tétraédriques (AX_4, AXY, AX_2Y_2, AXY_3, AY_4). Ces travaux ont porté sur des équilibres chimiques entre quatre molécules d'halogénures. Dans certains cas, il a été possible de suivre l'établissement des équilibres en fonction du temps.[107] Dans le même laboratoire, M. Delhaye a fait une étude d'ensemble des problèmes posés par l'enregistrement des spectres Raman. Il a notamment mis au point des montages à enregistrement très rapide permettant de suivre l'évolution des mélanges au cours des réactions chimiques.[108]

Bien qu'il ne s'agisse pas de spectroscopie à proprement parler, nous mentionnerons ici, diverses recherches sur l'anisotropie moléculaire étudiée au moyen de la diffusion Rayleigh dans les laboratoires de H. Benoit à Strasbourg et A. Rousset à Bordeaux, ainsi que par J. Tonnelat à l'Institut de Biologie Physicochimique.

(c) Spectres des Cristaux

Les interactions entre ondes électromagnétiques et ondes élastiques dans les solides ont été étudiées en grand détail par J. P. Mathieu et ses collaborateurs.[109] Lorsque les ondes élastiques correspondant aux modes normaux de vibration du cristal produisent une polarisation dipolaire de celui-ci, il peut en résulter des variations de la fréquence des ondes lumineuses absorbées ou diffusées. Ces variations dépendent de l'orientation relative du vecteur d'onde élastique et du vecteur polarisation. Dans les cristaux à symétrie élevée, certaines cessations de dégénérescence peuvent se produire. Ces divers effets ont été observés principalement dans les spectres Raman par L. Couture et J. P. Mathieu. D'autres preuves expérimentales en sont également données par la diffusion des rayons X ainsi que par l'absorption et la réflexion des radiations infrarouges.

Les spectres d'absorption, d'émission et de réflexion des cristaux dans l'infrarouge ont fait l'objet de nombreuses études principalement dans les laboratoires de J. Lecomte[100] et A. Hadni[110] ainsi que dans le laboratoire A. M. Vergnoux à Montpellier.[111]

(e) Mesures d'Indices de Réfraction

Des mesures d'indices de réfraction dans l'infrarouge ont été effectuées sur des solides et des liquides dans le laboratoire de J. Lecomte et sur des gaz au laboratoire de P. Barchewitz où la dispersion anomale de HCl a été mesurée par F. Legay entre deux raies de vibration-rotation consécutives au voisinage de ces dernières.[112]

G. Spectroscopie des Radiofréquences

Les méthodes optiques de détection de la résonance magnétique constituent depuis leur origine en 1949 un domaine de recherches qui s'est régulièrement développé en France, au laboratoire de l'Ecole Normale Supérieure.

Après les suggestions initiales de Bitter[113] soulignant

l'intérêt que présenterait une détection de la résonance magnétique dans les états atomiques *excités*, Brossel et Kastler[114] decrivaient la méthode de "double résonance." Très rapidement,[115] l'expérience apportait une confirmation expérimentale à ces prédictions. La technique était reprise et mise à profit dans divers laboratoires en Allemagne, en Angleterre et aux U.S.A.[116] Elle permettait d'obtenir des déterminations précises des durées de vie des états atomiques étudiés, la valeur des facteurs de Landé correspondants et la grandeur des intervalles de structure hyperfine. On a pu ainsi déduire de ces mesures les valeurs des moments quadrupolaires nucléaires des atomes alcalins que l'étude de la structure du niveau fondamental ne permet pas d'obtenir.

La méthode de "double résonance" était limitée à l'étude des niveaux que l'on peut atteindre par excitation optique d'une vapeur. En pratique même, elle n'a pu être appliquée qu'au niveau de résonance optique et dans le cas des alcalins, au deuxième niveau de la série principale.

Dès leur première publication, Brossel et Kastler[114] soulignaient que la lumière émise par l'atome excité par bombardement électronique dans l'expérience de Franck et Hertz est polarisée pour de nombreuses raies—C'est donc que les divers sous-niveaux Zeeman des états excités ne sont pas également peuplés par le bombardment électronique: une transition de radiofréquences entre ces sous-niveaux égalisant ces populations, ceci se traduit par une dépolarisation de la raie émise. Cette méthode est beaucoup plus souple que celle de double résonance. Elle permet l'étude d'un beaucoup plus grand nombre de niveaux. Elle a été beaucoup utilisée[117] par le groupe de l'Ecole Normale qui a ainsi obtenu de nombreuses valeurs de durée de vie et de facteurs de Landé pour les atomes Hg, ^{3}He, ^{4}He, Na, Cs, Zn, Cd. L'extension de cette méthode à d'autres atomes est à prévoir à brève échéance.

La méthode de double résonance ne s'applique pas à l'étude des états foundamentaux. Pour remédier à cet inconvénient, Kastler[118] imagina en 1950 le principe du "pompage optique"; l'atome, placé dans un champ magnétique absorbe de la lumière polarisée circulairement et retombe à l'état fondamental par émission spontanée. Il est facile de voir qu'au cours de ce cycle, on transfère à l'atome une partie du moment angulaire transporté par la lumière incidente: si la lumière incidente est circulaire droite, les atomes s'accumulent dans le sous-niveau Zeeman de l'état fondamental ayant le nombre quantique magnétique le plus grand. Si ce processus de pompage est plus rapide que celui-désorientateur-de la relaxation thermique, on aboutit à un état stationnaire où il existe, à la température ordinaire, de grandes différences de populations entre sous-niveaux Zeeman. De nombreuses variantes du cycle de pompage optique ont été décrites depuis.[119]

L'efficacité du pompage optique pour obtenir des orientations appréciables fut rapidement mise en évidence à Paris sur les atomes d'un jet de Na,[120] sur la vapeur saturante de Na[121] et sur la vapeur saturante en présence d'un gaz étranger.[122] Des recherches parallèles suivirent très rapidement dans d'autres laboratoires. Récemment, ces méthodes ont permis d'observer l'orientation nucléaire[123] de la vapeur de mercure (isotopes impairs) et d'étudier la relaxation de ces isotopes sur les parois de la cellule.

De nombreux problèmes ont été étudiés par le groupe de l'Ecole Normale en utilisant ces méthodes. Certains sont de spectroscopie pure: les études citées utilisant le bombardement électronique entrent dans ce cadre. On peut citer aussi le travail de Blamont[124] sur l'effet Stark du niveau 6^3P_1 de l'atome de mercure, par la méthode de double résonance. Cette étude a été faite sur les divers isotopes et a permis de voir l'influence du spin nucléaire sur les intervalles Stark.

Une autre classe de problèmes étudiés concerne les collisions. Les collisions d'un atome de mercure dans un sous-niveau Zeeman de l'état excité 6^3P_1 avec les atomes d'un gaz rare produisent des transferts vers les autres sous-niveaux Zeeman et réduisent par suite la durée de vie. L'élargissement correspondant (élargissement de Lorentz) a été ainsi mesuré.[125] Dé même Cagnac[123] a étudié les collisions qui désorientent un noyau de mercure (dans son état fondamental) lors d'un choc contre la paroi. Des études analogues sont en cours sur les atomes alcalins, lors de chocs sur des revêtements paraffiniques ou sur des enduits de silanes. Souvent l'origine de l'interaction responsable de la désorientation a pu être identifiée par une étude détaillée de la relaxation.

Une autre classe de problèmes étudiés concerne l'interaction du rayonnement électromagnétique avec les atomes.

C'est ainsi que plusieurs types de transition à plusieurs quanta ont êtê découverts et étudiés en détail. Dans le cadre de ces recherches, J. M. Winter[126] a fait le cacul théorique complet de ces phénomènes. Il a donné les formules donnant les formes de raies et celles des déplacements radiatifs très importants que subissent ces transitions. Des phénomènes analogues[127] sont observés actuellement dans le domaine optique en prenant comme source un laser; il semble que les formules de Winter sont applicables dans ce cas.

Un autre phénomène remarquable découvert par le groupe de l'E.N.S. est l'affinement des raies de résonance magnétique par diffusion multiple: dans une vapeur où la diffusion multiple est importante, on observe des raies dont la largeur est plusieurs fois plus petite que la somme des *largeurs naturelles* des niveaux d'arrivée et de départ. Ce phénomène, découvert par Blamont[124]

fut attribué par Brossel à la diffusion multiple, ce qu'une longue série d'expériences permit de prouver.[128] Brossel montra qu'une diffusion "incohérente" ne permet pas d'expliquer l'affinement des raies, alors que des affinements considérables résultent d'une diffusion "cohérente" dont il donna la définition. Le travail de thèse de Barrat[129] aboutit au calcul de phénomène dans le cadre de la théorie quantique des champs. Barrat mit au point le formalisme qui permet d'écrire la matrice densité du système d'atomes dans l'état excité en présence de photons de résonance optique et de radiofréquence. Il montra, en outre, que les éléments non diagonaux de la matrice densité décroissent avec des constantes de temps—"temps de cohérence"—qui sont ceux que permet de mesurer la méthode de double résonance et la méthode de Hanle. En présence de diffusion multiple, ces temps sont plus longs que la durée de vie et sont différents des "temps d'emprisonnement" (constantes de temps d'évolution des éléments diagonaux de la matrice densité).

Les faits précédents étaient les premiers exemples d'une série de phénomènes qui sont liés aux propriétés d'emission spontanée et d'absorption d'un atome placé par un champ de radiofréquence dans *une superposition cohérente d'états*. Entrent dans cette classe, les phénomènes de modulation[130] de la lumière absorbée (ou émise[131]) par un atome subissant la résonance magnétique dans l'état fondamental (ou excité).

En reprenant le formalisme de Barrat, Cohen-Tannoudji[132] a pu faire le calcul complet du cycle de pompage optique (en présence de radiofréquence) dans le cadre de la théorie quantique des champs. On peut ainsi prévoir—ce qui a été confirmé expérimentalement[133]—que les fréquences de résonance observées entre sous-niveaux Zeeman dépendent de la présence dans le faisceau lumineux pompant, de longueurs d'ondes optiques qui ne *sont pas* susceptibles de provoquer des transitions réelles de l'atome. Ces "shifts lumineux" liés aux transitions virtuelles, expliquent de nombreuses difficultés observées dans les horloges atomiques à pompage optique.

Le même théorie prévoit de nombreux autres effets liés à la circulation de la cohérence (éléments non diagonaux de la matrice densité) dans le cycle de pompage optique. Ces conclusions sont actuellement soumises au test de l'expérience et certaines ont été déjà vérifiées.

Soulignons enfin que l'extension des méthodes optiques de détection de la résonance magnétique à l'étude des impuretés paramagnétiques dans les cristaux à basse température a été entreprise à l'E.N.S. Un résultat intéressant[134] peut être rapporté: la résonance magnétique dans l'état fondamental de Cr^{+++} dans Al_2O_3 a pu être détectée par étude des variations de l'absorption (à résonance) pour une longueur d'onde λ quelconque à l'intérieur de la bande verte du rubis.

L'étude de l'intensité des résonances magnétiques observées, en fonction de la longueur d'onde λ a permis de mettre en évidence une structure de la bande beaucoup plus contrastée que celle résultant de l'étude de l'absorption direct. Il semble que cette technique soit appelée à se développer considérablement.

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Optics in Italy

Adriana Fiorentini

A brief review is presented of the work carried out in Italy in various branches of optics and related fields.

Introduction

Modern optics developed in Italy in the early 19th century, mainly in regard to theory and the construction of optical instruments. Most of the earlier opticists in Italy were astronomers; a few others pioneered in the design of optical instruments for topographical purposes.

Optical research was active around 1850, the period of Amici, Porro, and Riccò, but it gradually declined until, in the years preceding 1914, neither scientist nor organization contributed to the development of optics in Italy other than those optical industries founded at the end of the 19th century. The first organization devoted to optical research, the Laboratorio di Ottica e Meccanica di Precisione, founded in 1917, operated no more than a few years. Only personal contributions to optical research, outside any organized scientific body, were made in the following decade until a new organization, the Istituto Nazionale di Ottica, became active in 1927. This Institute was created for the purpose of promoting the development of Italian optical research and providing advanced instruction in the various branches of optics. It is still the only organization exclusively devoted to the study of optics in this country, although several other organizations contribute in part to the development of particular branches of optics: the research laboratories of the optical industries, the Physics Departments of some universities, the Center for the Study of Microwave Physics of the National Research Council and, for physiological optics, the Departments of Ophthalmology, Physiology, or Psychology of some universities.

The following sections contain a brief review of the work carried out in Italy in specific fields of optics. This review should in no way be considered as complete; it will only point out some of the highlights of optical development in Italy. In particular it does not consider research applicable to solid-state physics rather than to optics in the strict sense. For more detailed information on the subjects mentioned in this paper the reader will be referred to the original publications.

I. Geometrical Optics and Optical Design

A number of Italian scientists have contributed to the development of the theory of optical instruments since the early 19th century. Among them are Amici and Porro, whose works are so well known that they do not require to be mentioned here, and a few others, lesser known, such as Mossotti who, in his book on the theory of optical instruments,[1] presented a complete treatment of third-order aberrations and who first demonstrated the possibility of correcting both the spherical and sine aberrations of a cemented doublet (by the formula found later by Harting); Billotti[2] who studied trigonometrical ray tracing; and Ferraris who considered the cardinal properties of optical systems. More recently, geometrical optics and optical design have perhaps not been so generally cultivated in Italy as in other countries, although research of considerable interest was carried out during the period following World War II and in the last few years.

The design of a new Schmidt telescope, having only spherical surfaces, is due to Colacevich[3] who also contributed to the study of optical concentric systems[4] and proposed a new formula for the interpolation of the refraction index of glass.[5] Early studies on aspherical refracting surfaces were performed by Scandone.[6] Various papers by Toraldo di Francia deal with the correction or the calculation of some aberrations of particular optical systems[7,8] and with the variation of axial aberrations as a function of object distance.[9] Recently Cambi has developed a projective formula-

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tion of the problems of geometrical optics with an application to the design of a centered optical system.[10]

Substantial contributions to geometrical optics and optical design have been made by Morais. Besides various types of photographic lenses, range finders, and periscopes, Morais has designed wide-angle lenses for aerial photography (unpublished report), a particular photographic lens with a distortion not greater than 1 μ over a 30° field (to be applied to a bubble chamber), and a solar telescope.[11] He has also contributed to the study of concentric systems[12] and to the study of high-order aberrations,[13] has applied vector homographies to the design of optical systems,[14] and has derived a generalized formulation of Heath's law.[15] Many other papers by the same author deal with the particular problems of anamorphic systems, systems with variable focal length, etc.

Other contributions to optical design are mentioned in Section III.

II. Diffraction

The chief contributor to the study of optical diffraction has been Toraldo di Francia. In a number of papers he developed a new formulation of the fundamental problems of diffraction through the principle of inverse interference, postulated and demonstrated the existence of evanescent waves in diffraction, gave a satisfactory account for the anomalous propagation of waves, applied the Gibbs phenomenon to the theory of optical images and to contrast-phase microscopy, demonstrated that diffraction is not in general a reversible phenomenon in the thermodynamic sense, etc. Most of his earlier contributions to the development of diffraction theory are contained in his recent volume "La diffrazione della luce,"[16] a general introduction to light diffraction from the point of view of modern applications.

Toraldo has also shown the advantage of considering a third branch of optics, intermediate between geometrical optics and wave optics but having characteristic features of its own, which he called *parageometrical* optics.[17] Parageometrical optics has proved to be a valuable means of investigation in the field of microwaves.

A contribution of primary importance in the understanding of fundamental diffraction phenomena is also due to Toraldo di Francia, who demonstrated that no theoretical limit exists for the resolving power of an optical system.[18] This fact has been shown to be a necessary consequence of the role of evanescent waves in diffraction. The same author has also computed suitable amplitude and phase distributions on the pupil giving resolving powers much higher than the classical one.[19]

Some properties of diffraction gratings have been investigated by Ronchi, Scandone, Toraldo di Francia, and others. Some of this work is mentioned in the next section.

III. Applied Optics

Passing in rapid review the many topics pertaining to applied optics we shall first refer to the so-called grating-interferometer devised by Ronchi[20] whose theory and application have been widely treated in Italy. Soon after its conception, the grating-interferometer proved to be a successful means of progress, partly because of its interesting theoretical implications but also because of its practical use, a direct consequence of the simplicity of its application to testing optical instruments. A great deal of work was then devoted to the development of the Ronchi test; the main contributors have been Di Jorio,[21] Bocchino,[22] Bruscaglioni,[23] Scandone,[24] and Toraldo di Francia.[25] The exact theory of the grating-interferometer was later developed in a simple and elegant manner by Toraldo di Francia.[26]

In the field of optical instruments for astronomical purposes, mention should be made of several spectrographs designed and constructed in Italy which, if not completely original, at least present considerable improvements over the classical types. The solar spectrograph designed by Morais[11] and mounted at the Astrophysical Observatory of Arcetri is a modification of the classical Eagle type where the single mirror has been replaced by a Cassegrain-system with the advantage of a greater compactness of the whole instrument. Fracastoro has made use of a perforated grating in the design of a spectrograph to be applied to the Zeiss reflector telescope of the Lojano Observatory.[27] A high luminosity mirror spectrograph, whose optical system has been designed by Morais, presents a particular solution of the problems of flexures and of thermal isolation, due to Guidarelli.[28] The instrument contains a Cassegrain collimating system and a camera which consists of a catadioptric concentric system.

Considerable advance has been made recently in the design of optical instruments for topographical purposes, a field of research to which Italian researchers have devoted constant attention ever since the days of Porro. A high-precision automatic level has been recently conceived and constructed[29] which permits leveling operations with the accuracy of the order of 1 sec of arc.

Optical applications to photogrammetry are also being developed. Wide-angle objectives for aerial photography with very small distortion have been designed and the distortion measured by a new instrument.[30] Stereocomparators of extremely high accuracy have also been built.[31]

Some contributions have been made to the study of photographic emulsions as regards their performance

as receptors of optical images. The resolving power of photographic materials was measured independently from that of the objective lens by a resolvimeter designed by Bruscaglioni,[32] and measurements in a variety of experimental conditions were carried out by Bocchino.[33] Fracastoro also contributed to the theoretical and experimental investigation of some characteristics of photographic emulsions.[34]

IV. Physiological Optics

The study of vision is spread over a number of fields in both the physical and biological sciences; consequently it is difficult to make a comprehensive review of the work done in this field. An attempt will be made to mention at least the main sources of information.

A group of research workers at the Istituto Nazionale di Ottica has been working in the field of vision for the last ten years. Most of them are physicists and have investigated mainly the physical and psychophysical aspects of vision. In addition, electrophysiological and psychological phenomena connected with vision have been widely investigated.

Toraldo di Francia has emphasized the need for using wave optics instead of geometrical optics when dealing with the performance of retinal receptors. The analogy between retinal cones and microwave antennas suggested in particular a new interpretation of the Stiles-Crawford effect.[35,36] Toraldo has also pointed out the role of spacial and temporal gradients of retinal illumination in affecting visual response, starting a number of researches which have been carried on by his co-workers. Investigations by Lucia Ronchi and her collaborators cover a variety of subjects, namely, the readability of printed characters of various shapes,[37] the effect of mydriatics on some visual functions,[38] the directivity of retinal receptors,[36] the effects of possible rod-cone interaction at mesopic levels,[39–47] the speed of reading under critical conditions,[42–44] the effects produced by figures with quasi-perceptive contours,[45] etc. A great deal of work has also been done by Lucia Ronchi and her co-workers on the electroretinographic response to various types of time-varying stimuli[46–48] as well as on the possible interactions between electrical responses to stimuli of different wavelengths.[49,50]

V. Ronchi is responsible for a number of papers on some psychological aspects of vision, and his contributions to this field are summarized in a recent volume.[51] The author of the present review and her co-workers have contributed to the study of contour-contrast effects,[52–55] of some dynamic characteristics of vision,[56] and of binocular interaction.[57]

Most of the Italian contributions to the study of the physiology of the eye have been made by groups of workers in the Ophthalmological or Physiological Departments of certain universities. Mention may be made, for instance, of the investigations on the electrical response of the eye made by Wirth at the Ophthalmological Department of the University of Rome,[58] of a number of researches carried out at the University of Pisa by Focosi and his co-workers,[59–65] especially in the field of binocular vision, and of some investigations on the electroencephalographic response of various animals connected with visual stimulation, made under the direction of Moruzzi at the Neurophysiology Department of the University of Pisa.[66–68]

Psychological aspects of vision have been investigated at the Catholic University of Milan and at the Psychology Departments of the University of Florence, Rome, Palermo, etc.

V. Related Fields

In Italy, as anywhere else, considerable advance has been recently made in some fields of research which, if strictly speaking do not belong to optics, are at least related to it, either because their development has contributed to a new formulation of classical optical problems or because the problems they raise can be solved by methods very similar to those applied in conventional optics.

One of these fields is that of microwave physics. At the Centro Microonde C.N.R. in Florence, a group performing research in optical microwave systems has been constituted under the direction of Toraldo di Francia. The researches carried out by this group in the last few years have covered a variety of subjects. The methods of optical design have been successfully applied in the study of configuration lenses for wide-angle and high-speed scanning.

New types of perfect configuration lenses have been found and correction of spherical aberration of very simple microwave lenses have been obtained by lens combinations quite similar to optical doublets.[69–71] Concentric stigmatic systems of the Luneberg type have been widely investigated; the mathematical problem of finding all possible lenses of this type has been solved,[72] and a particular class of lenses has been described.[73,74] Some of these systems, having an outer spherical shell of constant index and an inner core of variable index, could also be used as microscope objectives for the infrared.[75] Lastly, stepped-zone mirrors for microwaves have been designed which operate both by reflection and diffraction.[76,77] Parageometrical optics has proved to be valuable in the treatment of these diffraction reflectors.

Another field which is increasingly related to optics is that of information theory. Among the studies carried out in Italy in this field, some papers by Toraldo di Francia deserve special consideration because they represent one of the first attempts to formulate anew

the central problems of optics according to the methods of communication theory. Two papers deal with the statistics of the optical images considered as stochastic sources[78] and the capacity of an optical channel in the presence of noise[79]; but the most important contribution to this field seems to be the exact formulation of the theory of resolving power, by means of the sampling theorem, made by Toraldo di Francia.[80]

The classical concept of resolving power has long enjoyed the attention of the optical school of Arcetri, and many objections have been raised, especially by Ronchi,[81] against the conventional way of defining it. A crucial argument against conventional resolving power has been presented by Toraldo, as reported above (see Section II). The new formulation of the theory of resolving power is based on the evaluation of the maximum amount of information which may be contained in an optical image. The degrees of freedom of an optical image are shown to be a finite number, while the number of degrees of freedom of the object is infinite. As a consequence, a large class of different objects may correspond to a given image, and the actual object cannot be recognized unless an infinite amount of information is available *a priori* for the observer. In particular, this holds for the resolution of two points.

In the field of practical applications of information theory reference will be made to a learning machine recently constructed in Italy,[82–84] the PAPA (Italian abbreviation for Automatic Programmer and Analyzer of Probabilities). This machine has been successfully applied to "read" and to recognize patterns.

A contribution to the development of the physics of radiation is contained in two recent papers where the method of evanescent waves is applied to the study of the radiation emitted by charged particles in uniform straight motion.[85,86]

VI. History of Optics

To conclude this review it seems worth mentioning that the study of the history of optics has recently received increasing attention in Italy, mostly as a consequence of the original work done in this field by Ronchi. His general history of optics recently appeared in its French edition,[87] while a number of papers by the same author deal with particular subjects of considerable historical interest.[88]

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US delegates to the Sixth Congress of the International Commission of Optics are W. Lewis Hyde (leader), R. C. Jones, and D. Z. Robinson, with alternates Mary E. Warga, Stanley S. Ballard, and G. Hass. For more information about the ICO Munich meeting, see page 252.

Optics in Japan: With Special Reference to the Study of Transfer Function and Its Application in Optical Industries

Hiroshi Kubota and Toshimitsu Asakura

I. Universities and Research Laboratories

Optics—applied optics in a broad sense, including its applications—is one of the most active fields of research in Japan. Almost all universities and laboratories are conducting research not only in theoretical optics but also in the optical structure of matter, in spectroscopy, in optical instruments, etc. The liaison organizations among research workers are the Physical Society of Japan, University of Tokyo, Bunkyo-ku, Tokyo (publishing the monthly *J. Phys. Soc. Japan*), the Society of Applied Physics of Japan, Department of Engineering, University of Tokyo, Bunkyo-ku, Tokyo (publishing monthly *Oyobutsuri—J. Appl. Phys., Japan*), and the Spectroscopy Society of Japan, Institute for Optical Research, Tokyo University of Education, Shinjuku-ku, Tokyo (publishing quarterly *Science of Light*), etc. The Optics Division of the Society of Applied Physics plans special optics editions of *Oyobutsuri* which are published twice a year. Approximately one third of the papers reported in the *Oyobutsuri* are on optics and its related fields. These societies publish their journals both in foreign languages and in Japanese (the papers written in Japanese carry English title, abstract, and figure captions). Abstracts of the papers in the above journals are published in *Science Abstracts*.

There are several government research laboratories where the general problems of optical instrumentation are treated: the Mechanical Laboratory (Sumiyoshi-cho, Suginami-ku, Tokyo); the Optical Instruments Center in the Osaka Industrial Research Institute (Ohyodo-ku, Osaka) at which problems of optical glasses are investigated; and optical metrology is studied in the Central Inspection Institute of Weights and Measures (Itabashi-machi, Itabashi-ku, Tokyo). Significant photometry programs have been developed at the Electrotechnical Laboratory (Nagata-cho, Chiyoda-ku, Tokyo) where the problem of the determination of an international unit for brightness and its maintenance have been treated. The Institute of Physical and Chemical Research (Komagome-Kamifujimai-cho, Bunkyo-ku, Tokyo) has developed programs on such subjects as the optical structure of matter, photoelasticity, etc.

The members of the National Committee of the International Commission of Optics are from the Optics Division of the Society for Applied Physics; this research committee on physics is actually a subdivision of the Japan Science Council. One of the authors (H. K.) is now its chairman.

II. Optical Industries

Many cameras produced in Japan are exported all over the world; particularly popular have been Nikon and Canon. There are more than 40 reliable camera companies including the Nippon Kogaku, K. K. (Japan Optical Industrial Company), and the Canon Camera Company. Those who are interested in the Japanese camera industry and in the cameras themselves should read the report, "Cameras from Japan,"* published by the Japan Camera Industry Association.

Besides cameras Japan produces every kind of microscope including phase and interference microscopes, binoculars, telescopes, optical measuring instruments, spectroscopic apparatus, and the like.

III. Cooperation between Universities and Industries

Close contact between universities and industry is desirable in order that the universities may advance their research in response to the industrial demand while the industry accepts the new ideas resulting from recent

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* This publication is available from the Japan Camera Information and Service Center, 389 Fifth Avenue, New York 16, N.Y.

research, thereby improving production. In Japan, the Camera Research Association exists to carry out this purpose. This Association was established by the leading camera makers several years ago and is at present financially supported by the government and the optical industry, to conduct joint research on common and basic subjects. The first piece of work chosen by this organization was the question of eliminating stain on the lenses, which is found during or after polishing. At present, the Association is studying a wide range of subjects, with special attention to lens problems such as the transfer function, lens polishing, the use of high-speed electronic computers, and problems of the effects of transmittance and lens flare in the fidelity of color photography. Subcommittees for each of these subjects consider methods by which research may be advanced.

The Association does not yet possess its own laboratory, and most of the work is carried out in the universities, government laboratories, and optical factories. This cooperation is producing excellent results. All the research problems under study could not be quoted in detail in this brief paper: if an attempt were made to introduce all Japanese optical research work and industries, this paper would be but an index. Consequently, we introduce in the following section, as a typical subject, studies on transfer function.

IV. Studies on Transfer Function

In the spring of every year, the Physical Society and the Society of Applied Physics are hosts to a joint meeting in Japan. At this meeting many important reports are presented on all aspects of science—usually more than 50 optics papers are included. Thus, new ideas are introduced and old concepts evaluated. In the area of optics and its related subjects there are more than 300 registrants, from all over the country, who participate in the discussions.

In 1957 this meeting included a symposium on "The Application of Information and Communication Theory in Optics," during which the fact that an optical system could be treated as a low-pass filter of spatial frequencies, was discussed. That was the beginning of the joint research on the transfer function in Japan. Until recent years, more emphasis was given to the study of its application to the evaluation of the optical systems and to the development of instruments for measuring the transfer function. New results have already followed the use of the transfer function for evaluating lens performance. Several new instruments to measure the transfer function have also been developed.

The recent spread of high-speed electronic computing machines makes it possible to introduce a new lens design procedure using spot diagram and transfer function and is, thus, contributing to the improvement of lens design techniques not only in quantity but also in quality. Electronic computers are already in use at several optical plants.

In Japan, the present trend is to bring theory and measurement techniques of the transfer function into practical use.

The following discussion is divided into three major subjects: (A) experimental studies, (B) theoretical studies, and (C) measurement methods and instruments of the transfer function, each of which has been investigated during the past few years.

A. Experimental Studies

Yukichi Ukita and Jumpei Tsujiuchi (*Government Mechanical Laboratory Sumiyoshi-cho, Suginami-ku, Tokyo*)[1] studied the use of the transfer function in the ordinary microscope to establish the relation between the illumination coherence and the image characteristics. The image characteristics of a Siemens star, due to the various stops of the condenser changing the coherence effect of illumination, show the relation between coherence and resolving power. The influence of the condenser's aberration on the image was also investigated with the concept of the effective source defined by H. H. Hopkins. It is clear that this influence appears when the condenser's aberration is large and the light source is small. A proposition for the tolerance of the condenser's aberration has been calculated.

In order to improve the aberrant images, researches have been conducted in the camera lens for the filter prepared by combining an amplitude filter and a phase filter. A study has been made of filtering techniques to restore the contrast in the image formed by means of a two-foci filter compensating the aberration of the objective. The improvement of the image damaged by the aberration of the objective has also been studied by using the method of spatial-frequency filtering, and its application limit was shown experimentally for the case of defocused images. Then the effect of the aberration may be completely removed by these two processes, using a filter to compensate the aberration and spatial-frequency filtering, without loss from the zero part of the transfer function of the objective.*

Kazuo Sayanagi† (*Canon Camera Co. Inc., Shimomaruko, Ohta-ku, Tokyo*)[2] proposed the concept of an "information volume" defined in the form,

$$V = \int_{-\infty}^{+\infty} \int R(\nu, \omega) d\nu d\omega$$

which is equivalent to the Strehl definition, and con-

* This work was partly carried out while one of the workers was at the Institut d'Optique, Paris.

† Present address: Institute of Optical Research, Stockholm 70, Sweden.

sidered as the measure of performance of the optical system. Here $R(\nu, \omega)$ indicates its transfer function. Based upon this concept, the camera lens was thoroughly evaluated from the theoretical and experimental points of view. Studies on information volume and resolving power of an ideal lens, photographic emulsion, and their combination led to the conclusion that the transfer function of photographic emulsion is given by

$$R(\nu, \omega) = \frac{1}{[1 + 4\pi^2\sigma^2(\nu^2 + \omega^2)]^{3/2}}$$

where σ is a constant characterizing the diameter of the diffusion of light in the emulsion. This agrees fairly well with the experimental results.

In most optical design processes, a set of aberration coefficients or a merit function obtained from ray tracing is used as a measure of image quality. The weight of each coefficient or traced aberration is of fundamental interest to optical designers, but is not currently known. K. S. is now devoting his attention to this point with the help of the transfer function, and developing its application to optical design techniques. (Several results have been already produced in this field, some of which were presented to the London ICO Conference on Optical Instruments and Techniques in July 1961.) With the object of obtaining a soft focus filter for a favorable soft focus effect and an effective filtering device to produce continuous tone image from any optical image of periodic structures (such as screen dots and line structures in television images), he was led to invent a phase noise filter called the "Contimat" which is now available (see Fig. 1).

Minoru Tamura (*Faculty of Technology, Chiba University, Matsude-shi, Chiba-ken*), *Hitoshi Ohzu* (*Department of Applied Physics, Waseda University, Shinjuku-ku, Tokyo*), *and Hiroshi Kubota* (*Institute of Industrial Science, University of Tokyo, Azubu-Shinryudo-cho, Minato-ku, Tokyo*).[3] Based on the fact that the autocorrelation function of the intensity distribution of a uniformly exposed photographic emulsion is equal to its transfer function, experimental measurements of the transfer function were performed using a recording optical autocorrelator constructed in the laboratory. The method of the transfer function measurement by means of a random chart was investigated and confirmed by experimental results.

Kobuyoshi Kimura (*Canon Camera Co. Shimomaruko, Ohta-ku, Tokyo*) *and Hiroshi Kubota* (*University of Tokyo*).[4] The coherency of light is changed when the coherent light is transmitted or reflected on the plane having a random coarse surface. An experiment demonstrating the effect of roughness on the coherence of light was carried out with the purpose of its quantitative description of the ground surface, and the results were compared with those to be expected from theoretical analysis.

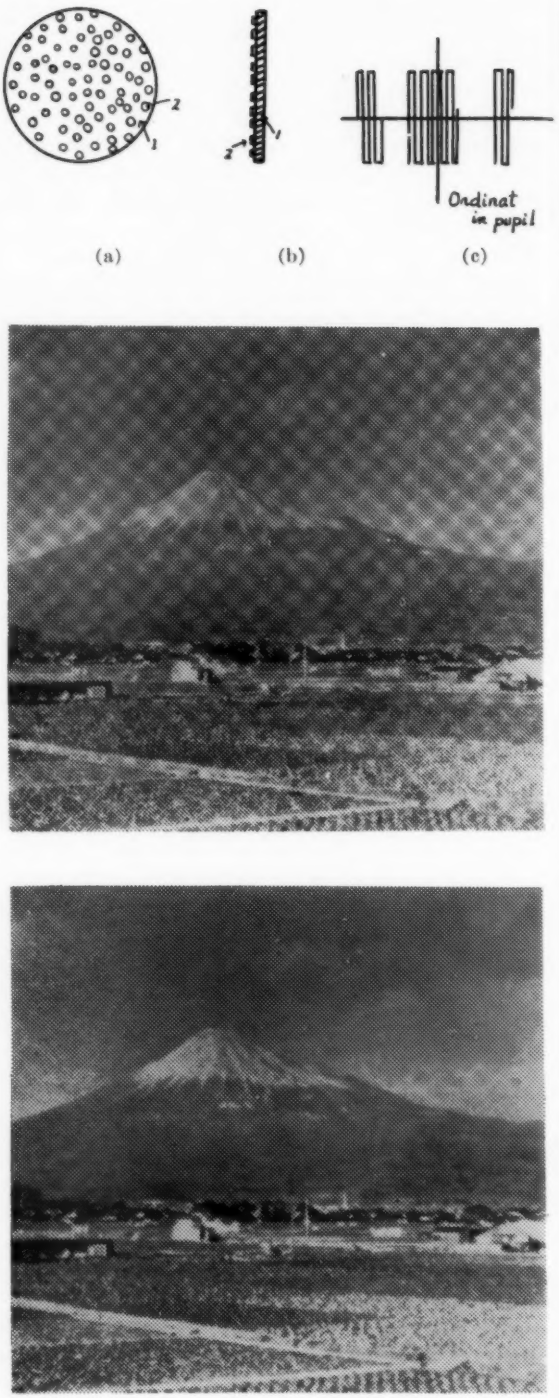

Fig. 1. Phase noise filter "Contimat." (a) a plane view of the filter, (b) a sectional view of the filter, (c) a diagram of pupil function combined with the filter, (d) removal of moiré pattern by the filtering effect.

Kojiro Kinoshita and Shizuo Tatsuoka (Technical Research Laboratory, Japan Broadcasting Corporation (NHK), Setagaya-ku, Tokyo) and Minoru Tamura (Chiba University).[5] One of the advantages of the transfer function lies in the fact that one is able to discuss, as one system, the net effect of objects, optical systems and receptors on the final image. Accordingly, one must have sufficient knowledge of the spatial-frequency spectra of the object. Following the usage of communication theory, Kinoshita and Tatsuoka attempted to investigate several spatial-frequency spectra of the objects and to study the ways in which these spectra are transmitted to our eyes with some modifications and restrictions such as lens, film, and photographic paper. Based upon their studies on the transmittance of the object spectra, a proposition was

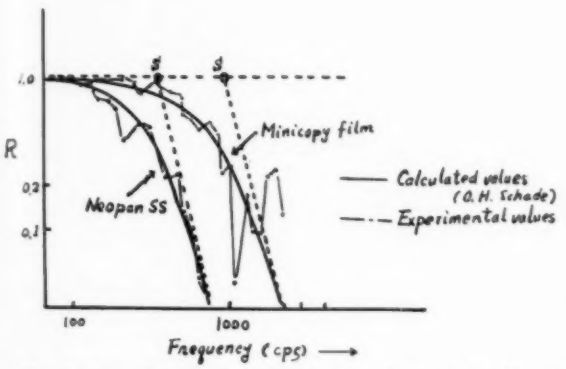

Fig. 2. Transfer functions, R, of the grain pattern. (Space constant factor S in frequency numbers: the crossed points between the lines parallel to the axis abscissa through the point $R = 1.0$ and tangential to the end part of the transfer function curves.)

taken to define a distortion factor of the lens which is considered as a parameter to evaluate the aberration concerned with the image angle. It gives the optimum correction of residual aberrations. Tamura obtained a great deal of experimental data with the investigation of several spectra of objects and films.

Shingo Ooue (Research Laboratory, Fuji Film Co. Ltd., Ashigara-gun, Kanagawa-ken)[6] has been at pains to describe the grain pattern of photographic materials. With the advent of transfer function techniques, he immediately took them into account and experimentally showed that most of the transfer functions of the grain pattern have the form shown in Fig. 2. From the nature of the curves of the transfer function he proposed the space constant factor S indicated in the figure, which shows the granularity of photographic materials. From the transfer function point of view he also found the relation between sharpness of the photographic image and the shape of characteristic curves of photographic materials, and examined the quality of tone

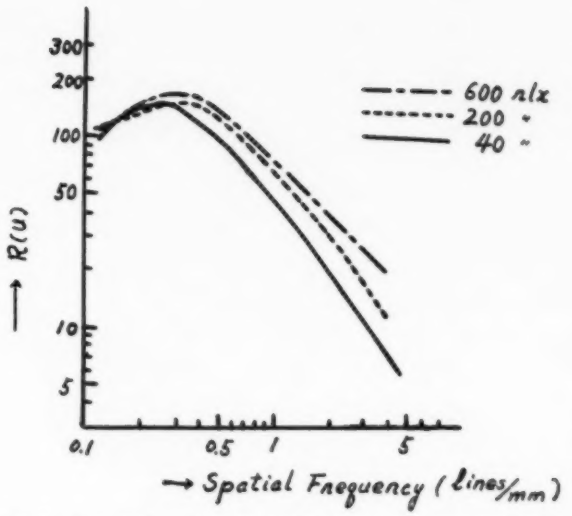

Fig. 3. Transfer functions $R(u)$ of the human eye, measured with varying luminance of the test field.

reproduction of the curve. A practical method to evaluate the granularity of subtractive color film by the Fourier technique method has been also reported. S. O. has also measured the transfer function of the human eye (Fig. 3.), and its measurement led to the new evaluation method of the grain pattern and of the sharpness of photographic materials.

Akira Hattori (Department of Education, Hiroshima University, Higashi-Senda-cho, Hiroshima-shi)[7] evaluated the performance of the focusing screens by the cosine Fourier transform of the line spread function. The relation between the transfer function and the characteristics of the focusing screen was studied in this way.

B. Theoretical Studies

Hideya Gamo (Faculty of Science, University of Tokyo, Motofuji-Cho, Bunkyo-ku, Tokyo).*[8] An optical system is a two-dimensional low-pass filter of spatial frequencies because there always exists some frequency which corresponds to the limit of resolution of the system. Since the complex amplitude over the image is the Fourier transform of the complex amplitude over the exit pupil of the optical system with a definite size, it is certainly band-limited, allowing one to use the sampling theorem on the complex-image amplitude. Thus, the intensity distribution over the image plane may be given by the discontinuous sampled values (the distance of the sampled value is inversely proportional to the numerical aperture), and finally by

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the matrix description. Gamo and Gabor, independently and simultaneously, demonstrated that image formation could be treated by matrix methods the elements of which are intimately related to the coherence function defined by E. Wolf. Gamo has developed the theory to the point where it now appears that the intensity matrix will play a role in statistical optics similar to that played by the density matrix of statistical mechanics. This analogy further defines the entropy of the light beam in terms of λ_i, the eigenvalues of the diagonalized matrix, as follows,

$$H = -\sum_i \left(\frac{\lambda_i}{\sum_j \lambda_j}\right) \log_2 \left(\frac{\lambda_i}{\sum_j \lambda_j}\right),$$

which is extremely interesting as a measure of the coherence of light. At present he is applying the matrix method to several problems. It should also be mentioned that Gamo and Gabor independently extended the sampling theorem to a corresponding theorem for the circular case.

Hiroshi Ito (*Faculty of Technology, Osaka University, Higashi-Noda, Miyakojima-ku, Osaka*).[9] As an applied mathematician H. I. investigated the derivation of the transfer function from the wave aberration function of the optical system, and presented an interesting paper on the transfer function of the optical system when the amounts of primary spherical aberration are not so large.

Iwao Ogura (*Central Research Laboratory, Hitachi, Ltd., Kokubunjimachi, Kitatama-gun, Tokyo*).[10] The method of stationary phase was applied to the asymptotic expansion developed by van Kampen and J. Focke. I. O. showed, for the large amount of aberrations, that the transfer function is represented as a sum of contributions from a number of critical points contained in the region of integration, and he carried out a rigorous analysis in the high-frequency region of the transfer function.

Kenro Miyamoto, Nippon Kogaku, K. K. (*Japan Optical Industrial Co., Ohi-Morimai-cho, Shinagawa-ku, Tokyo*) *and Hiroshi Kubota* (*University of Tokyo*).[11] The wave optical and geometric-optical transfer functions are given by

$$R_w(s,t) = a^{-1} \iint_{A_{\lambda s, \lambda t}} \exp\left\{\frac{2\pi i}{\lambda}\left[\phi\left(u + \frac{\lambda s}{2}, v + \frac{\lambda t}{2}\right) - \phi\left(u - \frac{\lambda s}{2}, v - \frac{\lambda t}{2}\right)\right]\right\} du dv,$$

$$R_g(s,t) = a^{-1} \iint_{A_{0,0}} \exp\left\{-2\pi i\left(s\frac{\partial \phi}{\partial u} + t\frac{\partial \phi}{\partial v}\right)\right\} du dv,$$

or

$$= a^{-1} \iint_{A_{0,0}} \exp\left\{-2\pi i(sx + ty)\right\} du dv,$$

where $A_{\lambda s, \lambda t}$ is the area common to two apertures in the frequency domain and where s and t are sagittal and tangential spatial frequencies, respectively, Miyamoto studied the relation between these two transfer functions for each aberration and derived interesting results (Fig. 4). The transfer function is theoretically very useful for the evaluation of lens performance. However, the fact that the generalized Seidel aberrations have been used as a favorable measure of image quality in usual lens design is because they may be calculated at the desk, and we may estimate lens quality at this stage of lens design. But the practical evaluation of the transfer function from design data (d, n, f, r, etc.) has not yet been investigated. In order to apply the transfer function technique to lens design, it is necessary to find an easy method for calculating the transfer function from the results of ray tracing. For this purpose it will be useful to change the geometric-optical transfer function instead of the wave-optical one into the following form:

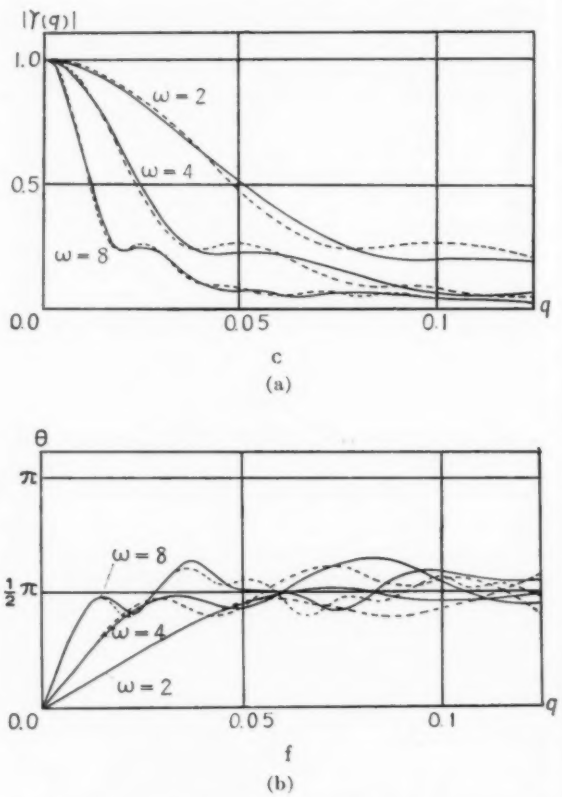
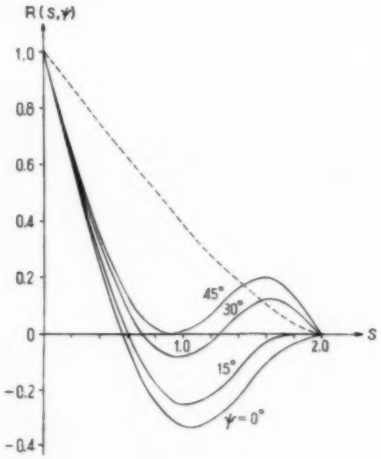


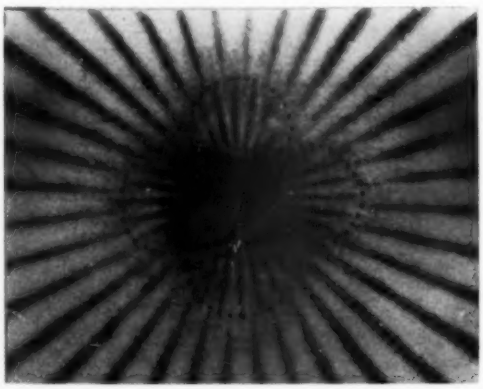
Fig. 4. (a) Transfer function $r(q)$ for the line image perpendicular to the meridional direction [coma $\phi = \omega\lambda v(u^2 + v^2)$]. (b) θ, phase shift of $r(q) = |r(q)| \exp[-i\theta(q)]$. Solid lines and dashed lines are the curves of wave-optical and geometric-optical transfer functions, respectively.

$$R_g(s,t) = \frac{1}{N}\sum_{i=1}^{N}\cos\left[2\pi(sx_k + ty_k)\right] - i\frac{1}{N}\sum_{i=1}^{N}\sin\left[2\pi(sx_k + ty_k)\right]$$

for which the spot diagram method may be applied; the application limit is also discussed. W. Lukosz independently derived the above equation. As Miyamoto showed the possibility of applying the above method in the optical system when the wave aberration is larger than several wavelengths, the method might be useful for the evaluation of photographic lens. Kubota calculated with Miyamoto the value of $R_g(s,t)$ given by the above equation for the case of a photographic lens with a relatively large aperture, and showed that it coincides fairly well with the results measured by Murata.



(a)



(b)

Fig. 5. (a) Transfer function of the polarizing microscope. (b) Photograph of the Siemens star (dotted lines are loci of zero of the transfer function).

Hiroshi Kubota (University of Tokyo) and Hiroyoshi Saito (Institute of Physical and Chemical Research, Komagome-Kamifujimai-cho, Bunkyo-ku, Tokyo).[12] The transfer function of the polarizing microscope when the Nicols are crossed is calculated and the amplitude of the diffraction image is shown to be

$$A(r,\theta) = \frac{\sin 2\theta \cdot J_2(2\pi ar/\lambda l)}{(2\pi ar/\lambda l)},$$

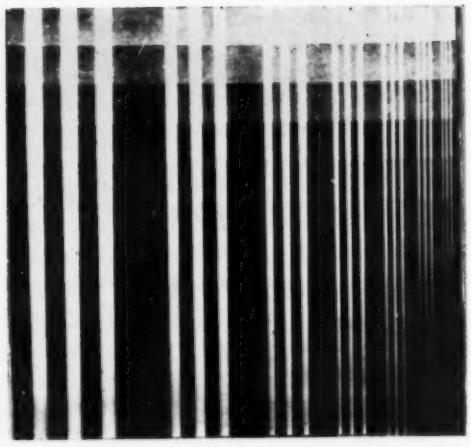
where r and θ are the polar coordinates in the image plane and λ is the wavelength. Diagrams are obtained by plotting the results showing the dependence of the transfer function on the direction (Fig. 5). The Siemens star was used for the experiment which showed good agreement with the theoretical results, expressing the reversal of contrast and spurious resolution.

Toshimitsu Asakura (Institute of Industrial Science, University of Tokyo, Azabu-Shinryudo-cho, Minato-ku-, Tokyo).[13] With O'Neill, he treated the problem of entropy loss as a function of defocusing in an optical system, and as the first step used the concept of entropy loss for the image evaluation. Also, annular and annulus apertures with spherical aberration were discussed from the transfer function point of view. Most of these studies were made during his stay at the Itek Laboratories, Lexington, Mass.

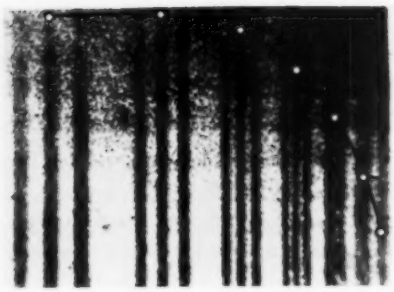
C. Measurement Methods and Instruments

The possibility of making use of the transfer function for lens evaluation depends upon the following conditions: (1) it is rigorously based on a theoretical foundation; (2) it can be obtained during the lens design processes; (3) its value can be easily and accurately measured. Lens evaluation methods heretofore took into account the Seidel aberration coefficients and the resolving power, each of which has its own merit. The transfer function is theoretically excellent for (1). With respect to (2) Miyamoto and Lukosz made it possible to calculate the transfer function in the process of optical design by means of a spot diagram. Accordingly, most effort should be directed towards (3). It is, however, hardly possible to develop an instrument of practical use in the optical industry without cooperation between university laboratories and the optical companies. Therefore the Japan Camera Research Association adopted studies of the transfer function for a research project, and is now strongly pushing forward a joint piece of work to develop both measuring instruments and the measurements of the transfer functions.

The following is a summary of the measurement methods of the transfer function which have been recently studied and developed in Japan. Some of them have been already incorporated into a working in-



(a)



(b)

Fig. 6. Direct-reading chart for the transfer function (Sayanagi). (a) Original chart. (b) Measured chart.

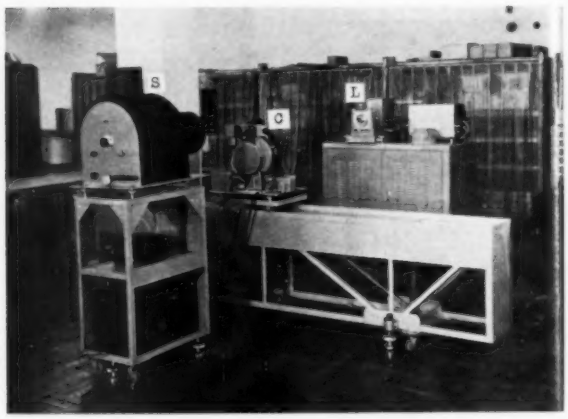
strument; others have been studied only in the laboratories.

Transfer function measurement methods

- Contrast measurement methods
  - Photographic method (a) (Sayanagi)
  - Television method (b) (Kinoshita Koana)
- Fourier transform methods
  - Integral method—Direct scanning method (c) (Murata, Ose, Suzuki)
  - Analysis method—Monofilter method (d) (Sayanagi)
- Cross-correlation between object and image—Photoelectric method (e) (Ohzu)
- Autocorrelation of the aperture functions—Interference method (f) (Tsujiuchi, Tsuruta)

(a) The photographic method is explained in the following way: take an image of the parallel-line test chart on a photographic plate and then measure its contrast with a densitometer. Instead of the usual parallel chart, Sayanagi[2] used a chart where the frequencies decrease horizontally and the contrast varies vertically. The transfer function is obtained by taking its photograph and combining the vanishing points of the contrast (Fig. 6).

(b) In the television method, the results of C. H. Schade are inversely used by forming a chart image on a vidicon tube screen and looking at it through the image-receiving tube screen (Kinescope) in a closed-circuit television system. At this time one of the scanning lines is chosen and its wave form observed with an oscillograph. Then the transfer function is obtained from the contrast recorded on the oscillograph. An instrument following the television method was constructed at the Technical Research Laboratory of the Japan Broadcasting Corporation (NHK) under the



(a)

(b)

Fig. 7. (a) General view of the transfer function-measuring instrument at the Technical Research Laboratory of the Japan Broadcasting Corporation (NHK). (b) The console. S—light source, C—chart, L—lens mounting, T, M—Braun tube, R—recorder.

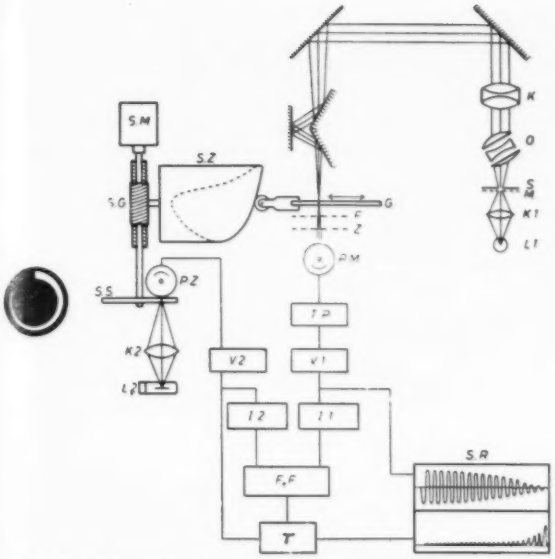


Fig. 8. Schematic diagram of the instrument for measuring transfer functions. L1, L2—lamp; K1, K2—condenser lens; K—collimator lens; M—diffuse plate; S—slit; O—lens under test; G—scanning chart (Foucault chart); F—interference filter; Z—beam chopper; S.Z.—cylindrical cam; S.G.—spiral wheel; S.M.—synchronous motor; S.S.—triangular chart; P.M.—photomultiplier; P.Z.—photocell; T.P.—view finder; V1, V2—amplifier; I1, I2—pulse former; F.F.—flip-flop; T—gate; S.R.—transfer function recorder.

direction of Kinoshita[14] and Koana (Department of Science, University of Tokyo, Bunkyo-ku, Tokyo) (Fig. 7).

(c) Kazumi Murata (Osaka Industrial Research Institute, Ohyodo-ku, Osaka)[15] studied the transfer function measurement instrument based on the direct scanning method with the use of one test chart. Figure 8 shows the block diagram including the optical and electrical systems in his instrument. For measuring the transfer function curves simultaneously and quickly, several new methods are used in this instrument, among which are employed a Foucault grating with a varying grating-constant, a cylindrical cam for scanning with varying velocity, and a pulse circuit for phase detection. It is understood that, using this instrument, less than one minute is needed to measure the modulus and the phase of the transfer function. An example of the actual measurements with the instrument stated above is shown in Fig. 9 where the transfer function is given by taking an envelope of the amplitude appearing in (a) and (b) which indicate a phase recording. The instrument made by Murata is suitable for use in laboratories, for closely examining manufactured goods or prototypes. This instrument is put on the market by the Olympus Optical Company (Hatagaya-Haramachi, Shibuya-ku, Tokyo) (Fig. 10).

On the other hand, Teruji Ose (Institute of Industrial Science, University of Tokyo, Azabu-Shinryudo-cho, Minato-ku, Tokyo)[16] made a measuring instrument of the transfer function, based on the same principle used above, but using two sine charts moving in the opposite directions as originally suggested by R. L. Lamberts. It thus became possible for the outputs of scanning to be added and subtracted from each other by the light modulation technique. Consequently the Fourier cosine and sine transforms of the line images are recorded, from which the phase function is obtained. Figure 11 (a) is a general view of this instrument and Fig. 11 (b) shows a recording example in which the first picture shows the Fourier sine transform and the second the Fourier cosine transforms. This instrument is ideal for quickly examining many samples.

The transfer function measurement by the direct scanning method using one chart is also being studied in the laboratory by Tatsuo Suzuki (Faculty of Technology, Osaka University, Higashi-Noda, Miyakojima-ku, Osaka).[17]

(d) This is a simple example demonstrating the monofilter method by Sayanagi[18] who used an edge instead of a slit.

(e) Following the principle of the cross-correlation between object and image, Ohzu (Department of Applied Physics, Waseda University) constructed an instrument for measuring the transfer functions with the use of a random chart. This instrument is useful for adjustment operations in the optical industry.

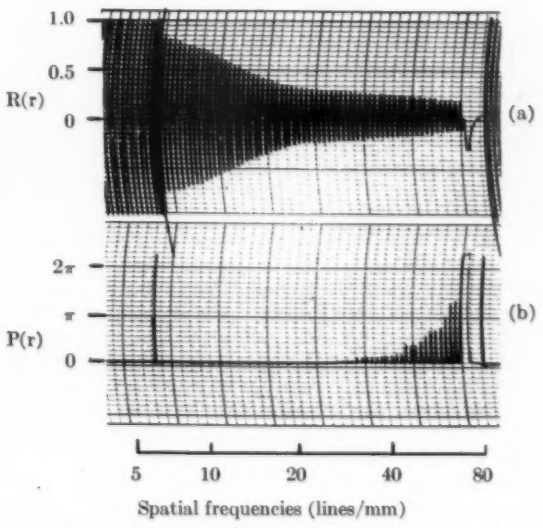
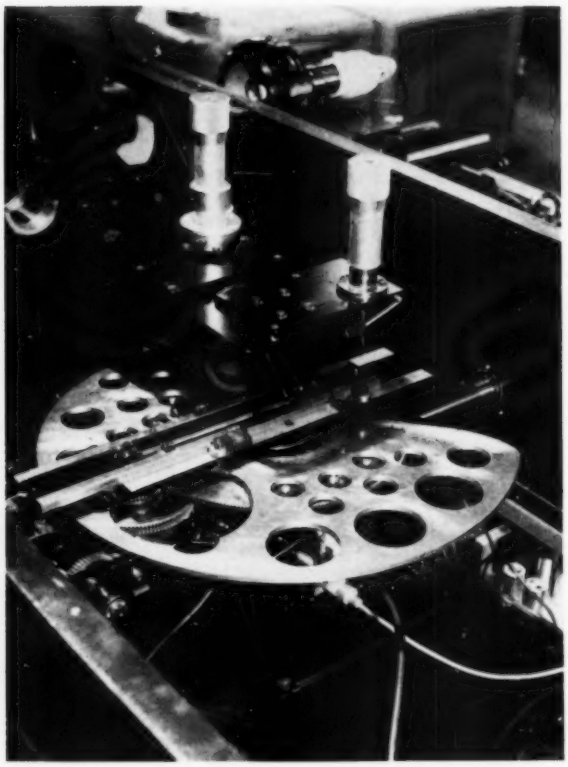


Fig. 9. Recordings of transfer function. (a) Amplitude $|R(r)|$. (b) Phase $P(r)$.

(a)



(b)

Fig. 10. (a) Transfer function-measurement instrument constructed by the Olympus Optical Company. (b) Its inner part (a cam to make recordings linear with respect to spatial frequencies).

(f) It is known theoretically that the transfer function is given by measuring the autocorrelation of the aperture functions. Based on this idea and with the help of interference techniques, studies on the measurement of the transfer function have been made by Jumpei Tsujiuchi (Government Mechanical Laboratory) for the evaluation of photographic lenses, and by Tadao Tsuruta, Nippon Kogaku, K.K. (Japan Optical Industrial Co., Ohi-Morimai-cho, Shinagawa-ku, Tokyo) for that of the microscope objectives. In particular, although the transfer functions of the microscope objectives have been theoretically discussed, it is very hard to obtain these transfer functions experimentally. Tsuruta[19] has been successful in the transfer function measurement of the microscope objectives with the use of a shearing interferometer. Figure 12 shows the sheared interferograms of wave fronts for the aberration-free and aberrant systems, which are obtained by birefringent systems in this instrument.

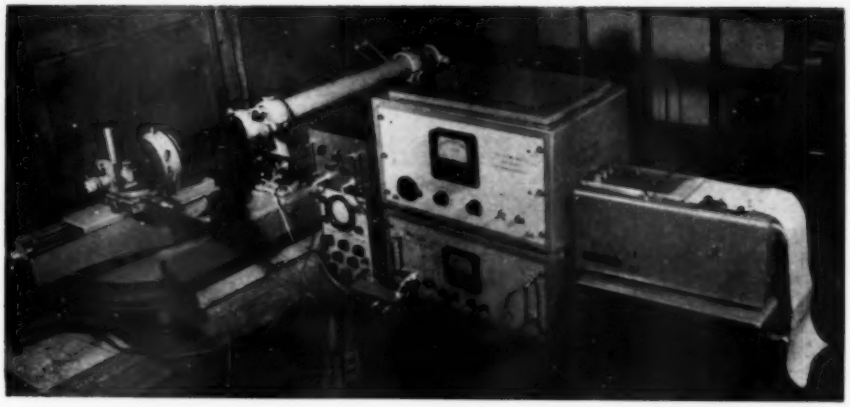
V. Industrial Standards

For some time, the transfer function has been known to be useful from the theoretical point of view as a method of lens evaluation. In recent years a great deal of effort has been devoted by many countries to the study of the transfer function and its practical applications in the optical industry. In the near future the transfer function is to be used for evaluating lens performance and for quality control with (or instead of) resolving power used so far to indicate the quality of lenses. For this reason a Subcommittee for lens evaluation was established by the International Commission of Optics, and its members are at present preparing to recommend that every country accept the new idea of the transfer function and put it into practical extensive use in optical industries. Although resolving power has been useful for certain cases and is of considerable interest, its value is dependent upon the conditions of observation and it is not always a well-defined physical quantity. It is, therefore, easily misunderstood without careful treatment, which leads one merely to "a play of resolving power." It might be proper that, in the field of lens evaluation, the transfer function be stipulated an International Standard. Pursuing this line of thought, the lens testing method section of the Japanese Industrial Standards Committee, whose chairman is one of the authors (H. K.), is considering (in cooperation with the Camera Research Association) the acceptance in the near future of the transfer function as a Japanese Industrial Standard. To avoid a big jump from the present resolving power to the use of the transfer function, a move in this direction would be the measurement of the resolving power by using as many contrast charts as possible. This is due to the fact that, to increase the number of those charts is naturally equivalent to using the transfer function for the measurement. Thus, as the first step in this direction, the Committee is considering changing "To test the resolving power by the use of the high contrast chart *or* of the low one,"

Fig.

Fig.
with

(a)



(b)

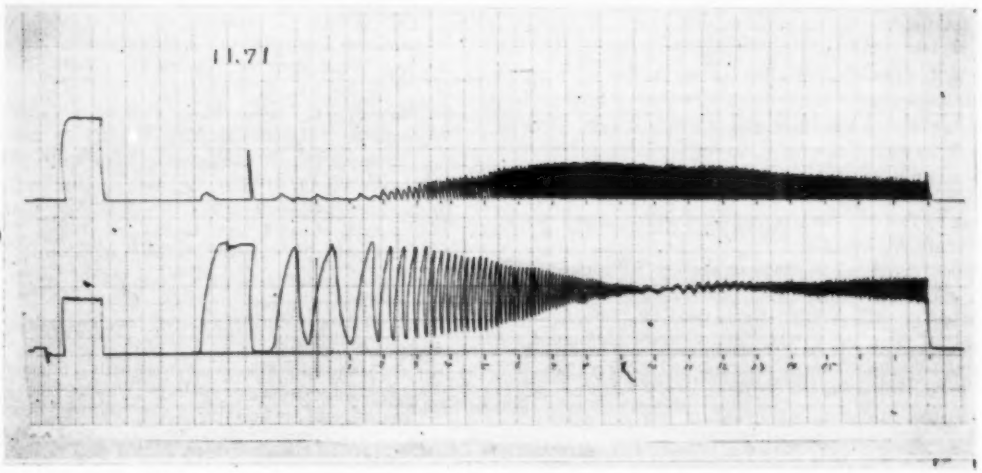


Fig. 11. (a) General view of the instrument for measuring transfer functions made by Ose at the Institute of Industrial Science, University of Tokyo. (b) Recording examples.

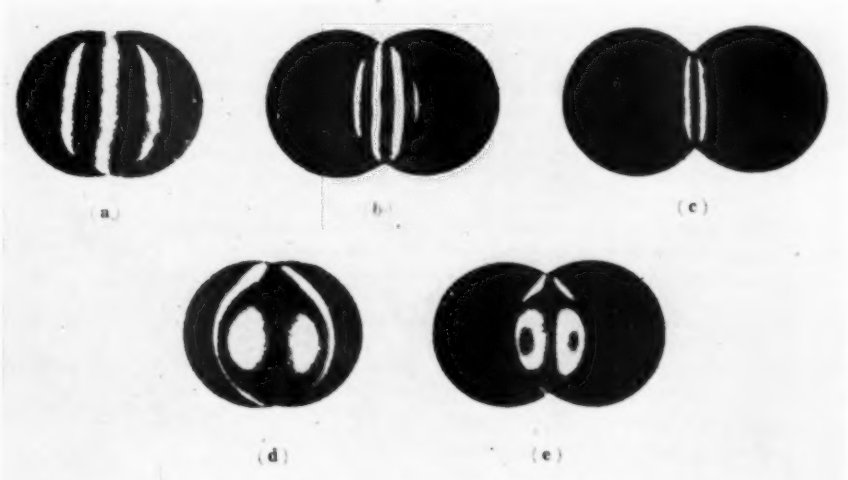


Fig. 12. Sheared interferograms of wave fronts: aberration-free system for (a) $s = 0.5$, (b) $s = 1.0$, and (c) $s = 1.5$, and system with primary spherical aberration 2.0λ for (d) $s = 0.5$ and (e) $s = 1.0$, where s is the distance between the centers of sheared circles.

to "To test the resolving power by the use of the high *and* low contrast charts."

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Ōyōbutsuri; The Physical Society of Japan and the Society of Applied Physics, Japan, have jointly announced that a new journal, *Japanese Journal of Applied Physics,* will be published monthly under their joint aegis. The first issue of this journal will appear in July 1962 and papers are to be published in English, French, and German.

At the same time the Society of Applied Physics, Japan, will continue to publish the established journal, *Ōyōbutsuri,* whose English name used to be the *Journal of Applied Physics, Japan.* To avoid confusion the existing journal will be called "Ōyōbutsuri" in both English and Japanese after 1962 and will publish only in the Japanese language after July 1962.

Spectroscopy for Solid-State Optical Masers

Satoru Sugano

A brief account is given of the spectroscopy of excitation processes in semiconductors, rare earth ions, transition metal ions, and actinide group ions in ionic crystals, from the standpoint of applying solid-state optical spectra to optical masers.

I. Introduction

Schawlow[1] has pointed out several spectroscopic characteristics which should characterize solid-state optical maser materials. They are as follows:

1. A sharp fluorescence line.
2. A relatively strong absorption band through which energy can be supplied to a crystal in an efficient way.*
3. A good quantum efficiency for the fluorescence (here the quantum efficiency means the ratio of the number of photons emitted in the fluorescence line to that absorbed in the band).
4. A lower state which can be depopulated at least at low temperatures.

If these are assumed to be the requirements for optical maser materials, then only a rather limited number of materials are found to satisfy these requirements. Let us consider the first requirement assuming that the line width should be of the order of magnitude of 1 cm^{-1}. Then some of the conceivable solid-state fluorescence spectra satisfying such a requirement are:

1. Moving or trapped exciton fluorescence.
2. The fluorescence of rare earth (lanthanide group) ions in ionic crystals.
3. The fluorescence of transition metal ions in ionic crystals.
4. The fluorescence of actinide group ions in ionic crystals.

In the following, we shall briefly describe these four kinds of spectra, always keeping in mind their possible application to optical masers. In order to simplify the discussion, no attention will be paid to the fourth requirement; this requirement need not always necessarily be satisfied, although it surely helps the onset of maser oscillation.

The author was on leave of absence from the Institute for Solid-State Physics, Tokyo University, Tokyo, Japan, while this work was done in the Bell Telephone Laboratories, Murray Hill, New Jersey.

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* Some other methods are conceivable besides optical pumping to supply energy to crystals. When these other methods are employed, this term may be omitted.

II. Exciton Fluorescence

Sharp exciton fluorescence lines have been observed in silicon, and also in cadmium sulfide, although the origin of the observed sharp fluorescence line in CdS crystals has not so definitely been ascribed to excitons.[2] For the exciton fluorescence in Si, reference should be made to Haynes' work.[3]

According to Haynes' interpretation, the dashed trace in Fig. 1 indicates radiation induced by recombination of excitons with the simultaneous photon and phonon emission. The solid trace indicates additional fluorescence observed in Si with arsenic impurities. Two conspicuous lines of the latter fluorescence are ascribed to recombination of excitons trapped in a complex center involving singly ionized arsenic impurities plus two electrons and a hole. Such excitons immobilized by impurities are sometimes called simply "impurity excitons" or, according to Lampert's terminology, "effective-mass-particle complexes." The line width of the impurity exciton fluorescence in Si is less than 4 cm^{-1}. The sharpness of the line can be ascribed partly to immobilization of excitons. The line width of the moving exciton fluorescence is broader than that of the impurity exciton fluorescence because of the thermal kinetic energy.

In CdS crystals, very narrow fluorescence lines have also been observed in the visible region. Some are supposed to be due to recombination of moving excitons and some are supposed to be due to impurity excitons. The line widths are so narrow that the Zeeman effect may be observed.[2]

An advantage of using exciton fluorescence lines for

optical masers* comes not only from the sharpness of the spectral lines but also from the coexistence of a very strong absorption band, called a fundamental absorption band, through which photon energy can easily be supplied to the crystal.

A remaining problem connected with the applicability of exciton fluorescence to optical masers is whether or not it satisfies the third requirement, i.e., whether the supplied photon energy is efficiently converted into the fluorescence of interest. Such a problem in Si has been extensively studied by Haynes *et al.*[4] The competitive processes in perfect pure semiconductors are radiative and nonradiative recombination of free electrons and holes and of excitons. Since a cross section of the nonradiative multiphonon process would not be large because of the relatively large energy gap, a fairly good quantum efficiency for the exciton fluorescence might be expected in perfect crystals. In imperfect crystals, the other competitive processes through imperfections may take place. Therefore, in order to obtain a good quantum efficiency for some specific exciton fluorescence line, it is necessary to suppress the other undesirable nonradiative and radiative processes by controlling imperfections in the crystals.

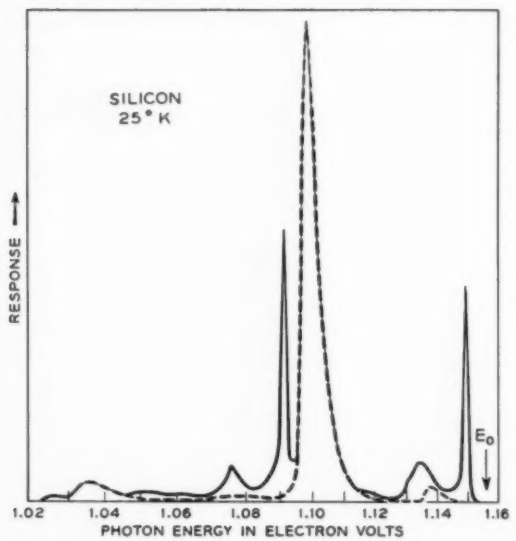


Fig. 1. Spectrometer response versus the energy of the photons for two silicon crystals: (1) A specimen containing a negligible amount of impurity, shown by the dashed trace. (2) A specimen containing 8×10^{16} cm^{-3} arsenic atoms, shown by the solid trace (Haynes[3]).

* Several schemes of using semiconductors for optical masers have been considered by W. S. Boyle and D. G. Thomas (private communications) and also by others.

III. Fluorescence of Rare Earth Ions

It is well known that crystals containing rare earth ions show many sharp fluorescence lines, and that these lines are due to transitions within the incomplete $4f$ shell. Since the effects of the surroundings for the f electrons are shielded by outer $5s$ and $5p$ electrons, the spectra resemble those of the free ions. Thus sharpness of the lines can be easily understood. The present status of the rare earth spectroscopy is fully described by McClure in his review article.[5] It will require very laborious experimental and theoretical works to clarify the rare earth spectra. However, it is considered, particularly by Dieke's group,[6] that this work will probably be completed fairly soon, at least for trivalent rare earth ions.

The oscillator strengths of these lines are very small, in many cases much smaller than those of the crystal field bands of transition metal ions which will be discussed in the next section. The reason is that asymmetric perturbations, which allow otherwise parity-forbidden electric dipole transitions, are also shielded by the outer electrons. The asymmetric perturbation may be instantaneous asymmetric distortions of a lattice by certain modes of vibrations or static asymmetric crystal fields naturally associated with some crystals of lower symmetry. Such weakness of the spectral lines is unfavorable to the optical maser application only because of the second requirement. As an example of trivalent rare earth ion spectra, both the absorption and fluorescence spectra of the $KEu(WO_4)_2$ crystal measured by Wood are given in Fig. 2(a) and Fig. 2(b), respectively.

However, it should be noticed that the statements hitherto given are only applicable to the infrared and visible spectra of trivalent rare earth ions and not to the spectra of divalent rare earth ions. In the divalent ions, relatively strong absorption bands exist in the vicinity of the group of sharp lines. These bands were found initially by Butement[7] in divalent europium, samarium, and ytterbium. The bands are tentatively assigned to transitions from the $4f$ to the $5d$ orbital which are parity-allowed. This assignment is considered reasonable for several reasons. One of them is as follows: Lowering of the $5d$ orbital relative to the $4f$ orbital may be expected when we go from the trivalent to the divalent ions. Actually, in the neutral atoms, some electrons are accommodated in the $6s$ and sometimes in the $5d$ orbital instead of all electrons being accommodated in the incomplete $4f$ shell.

The sharp lines of the divalent ions are reasonably assigned to transitions within the $4f$ shell as in the case of the trivalent ions. Between the states with the f^n and $f^{n-1}d$ configurations, there is no interaction such as the Coulomb and spin-orbit interaction, but asymmetric perturbations mix these states with each other. Therefore we can expect fairly large oscillator strengths

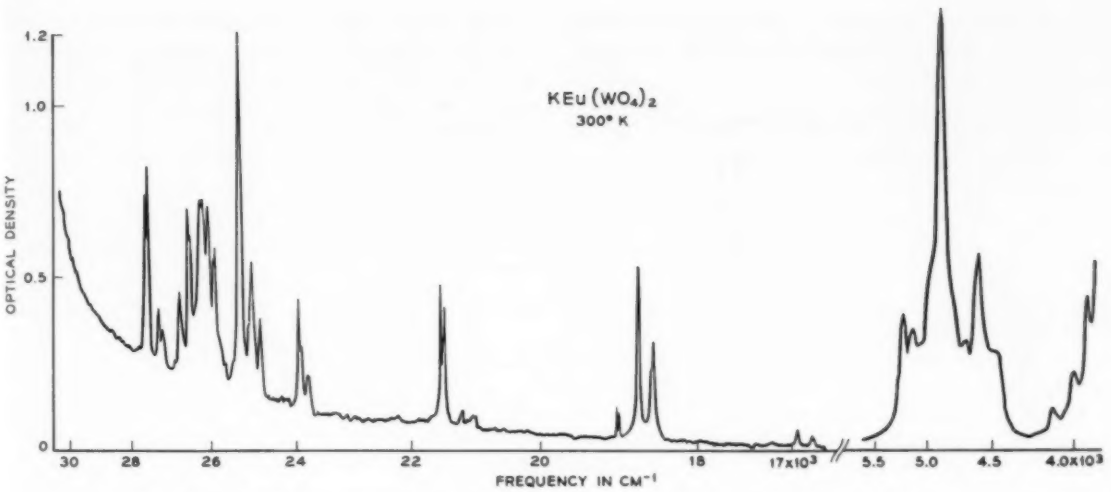


Fig. 2 (a). The absorption spectrum of the $KEu(WO_4)_2$ crystal (D. L. Wood, unpublished).

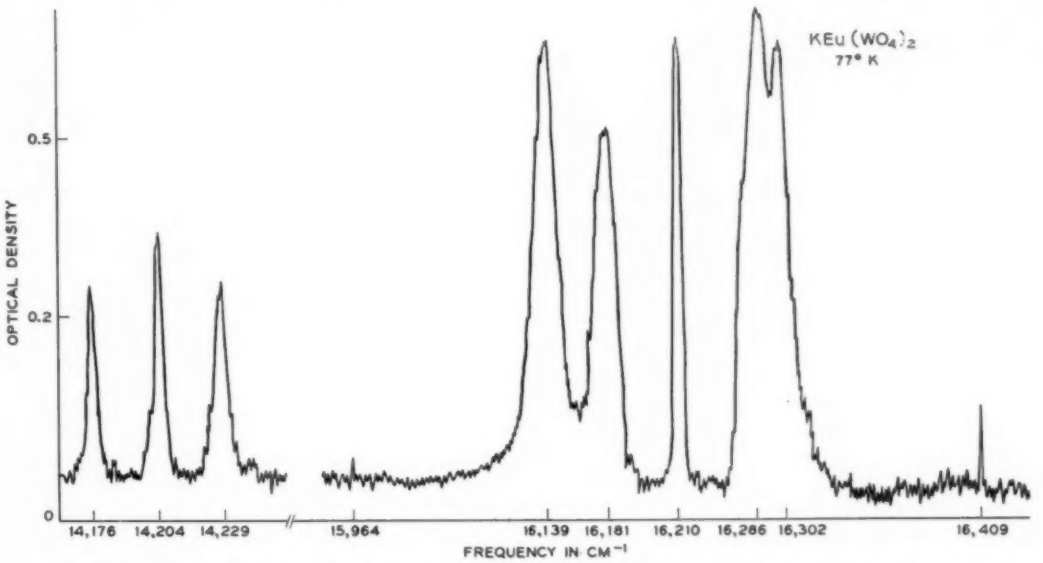


Fig. 2 (b). The fluorescence spectrum of the $KEu(WO_4)_2$ crystal (D. L. Wood, unpublished).

even for transitions within the $4f$ shell. The oscillator strengths of the order of magnitude of 10^{-4} have been observed for the group of lines by Feofilov[8] and Garrett *et al.*[9] In order to assist in understanding the general features of the divalent ion spectra such as coexistence of strong broad absorption bands and sharp lines, the observed absorption and fluorescence spectra of $CaF_2:Sm^{2+}$ are given in Figs. 3(a) and 3(b), respectively.

These features of the divalent ion spectra are favorable for optical maser application. Actually Sorokin and Stevenson,[20] and also Garrett *et al.*,[9] have observed maser oscillation in the $CaF_2:Sm^{2+}$ crystal. Simply speaking, their success can be partly ascribed to the lowering of the $5d$ orbital energy relative to the $4f$ orbital energy, which makes strong broad bands appear in the vicinity of sharp lines.

The problems relating to the requirement of high quantum efficiency do not seem so serious once the supplied energy is delivered to the initial state of the fluorescence. Nonradiative dissipation of the supplied energy in transitions within the $4f$ shell may be considered to occur at a small rate because of the weak coupling of the $4f$ electrons with the lattice. Nonradiative decays from the $f^{n-1}d$ states to the f^n states could occur with a fairly large probability with the

aid of odd parity perturbations. This will be discussed later together with the nonradiative process in transition metal ions in crystals.

IV. Fluorescence of Transition Metal Ions

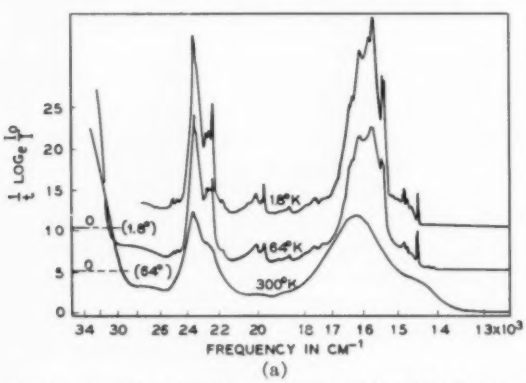
In some crystals involving transiton metal ions, namely, the first transition metal ions, we can observe gaslike spectral lines besides several broad absorption bands. The origin of these spectra is now well understood.[5,10] The gaslike lines are assigned to transitions within the states with the same electron configuration specified by $t_2^{N-n}e^n(n \leq N, n = 0, 1, 2, 3, 4)$ for N electron systems. The absorption bands in cubic crystals are identified with transitions exciting one electron from the t_2 molecular orbital to the e orbital. The t_2 and e orbitals are considered, to the first approximation, to be two quantum orbitals in a cubic field arising from the d orbital of free ions. The energy of the t_2 orbital is raised above that of the e orbital by interaction of the d electron with the cubic crystal field. Therefore, the transition energy from the t_2 orbital to the e orbital involves this interaction energy. Broadness of the absorption bands is considered to be due to the fluctuation of the crystal field by thermal vibrations. A detailed consideration shows that, even at zero temperature, the zero-point vibration can produce the observed magnitude of the bandwidth.[11] On the other hand, the separation of the multiplets with the same electron configuration $t_2^{N-n}e^n$ is determined by Coulomb interaction between the electrons of interest. Therefore, the separation is independent of the fluctuation of the crystal field. This is the reason why such sharp lines are observed even in the system where strong coupling is expected between chromophoric electrons and a lattice.

Unfortunately, only a few fluorescence lines have been observed in the transition metal ion systems, although many sharp lines have been found in absorption. Nevertheless, it is speculated that, when the fluorescence is observed, it will take place mainly from the lowest excited state. This speculation has no definite theoretical foundation, but it helps us to go one step further. For the purpose of picking up the transitions which could possibly give sharp fluorescence lines, let us assume the speculation to be correct and apply at the same time the previously mentioned principle of assigning the gaslike spectral lines. Then, it turns out that the following transitions in a very strong cubic crystal field can give sharp fluorescence lines:

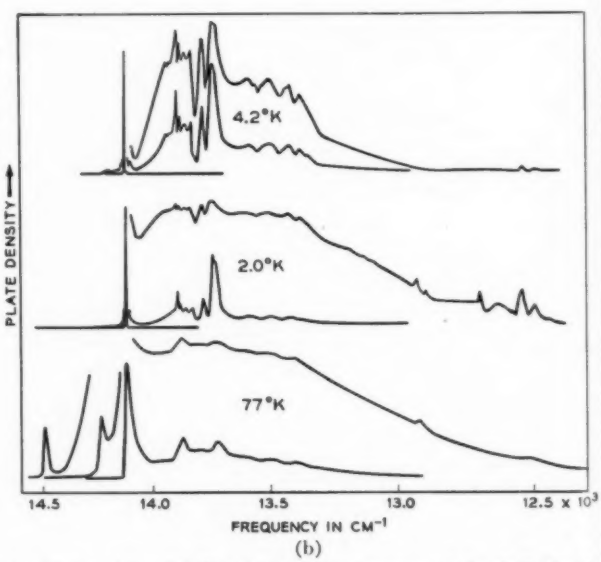
Systems	Transitions
d^2, d^4	^1E, $^1T_2 \rightarrow {}^3T_1$
d^3	^2E, $^2T_1 \rightarrow {}^4A_2$
d^5	$^1E \rightarrow {}^3A_2$

The d^4 and d^5 systems have not yet been found in a sufficiently strong cubic field to be certain that the listed excited states are the lowest ones. A typical example of the d^2 system is the trivalent vanadium ion in the Al_2O_3 crystal,[12] where the cubic field is sufficiently strong. Sharp fluorescence lines are expected in the near infrared region, but no such fluorescence has yet been reported. Trivalent chromium ions—the d^3 system—are usually found in strong cubic fields. The sharp fluorescence lines which have been identified or might be identified with the $^2E \rightarrow {}^4A_2$ transition[13,14] have been observed in a number of crystals.[15] As a typical example of transition metal ion spectra, the absorption and fluorescence spectra of ruby are given in Figs. 4(a) and (b), respectively.

The coexistence of absorption bands and sharp fluorescence lines in the transition metal ion spectra satisfies the first and second requirements to some extent. The oscillator strengths of these bands are



(a)



(b)

Fig. 3. (a) The absorption spectrum of the CaF_2:Sm^{2+} crystal (Garrett, *et al.*[9]). (b) The fluorescence spectrum of the CaF_2:Sm^{2+} crystal (Garrett *et al.*[9]).

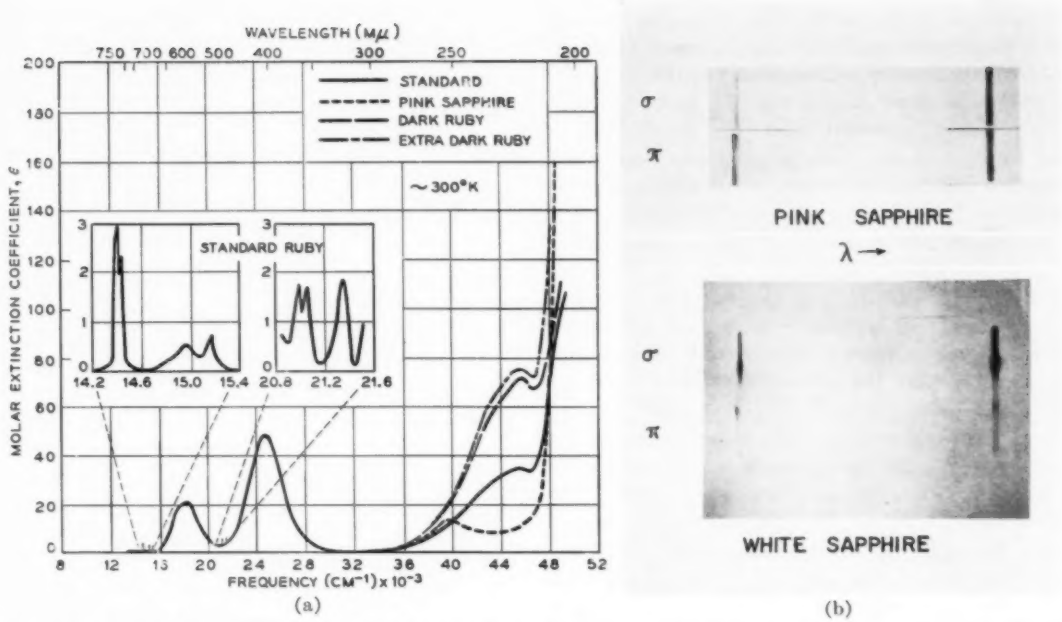


Fig. 4. (a) The absorption spectrum of the $Al_2O_3:Cr^{3+}$ crystals (D. M. Dodd, unpublished). (b) The most conspicuous fluorescence lines, R_1(14,421 cm^{-1}) and R_2(14,450 cm^{-1}) of the $Al_2O_3:Cr^{3+}$ crystals (D. L. Wood, unpublished).

of the order of magnitude of 10^{-4} or 10^{-3} and their broadness is convenient for optical pumping.

The remaining problem is concerned with the quantum efficiency of the fluorescence. In what follows, discussion on this problem will be given by taking a particular example of the trivalent chromium fluorescence. In Fig. 5, the pertinent curves of the trivalent chromium states in a cubic field are illustrated schematically in a conventional one-dimensional configuration coordinate. We may regard the coordinate Q as the distance between the chromium and the nearest neighbor ions. The observed fluorescence line comes from that $t_2^3\ ^2E$ state, and the broad absorption bands in the green and blue region correspond to transitions to the $t_2^2\ e\ ^4T_2$ and $t_2^2\ e\ ^4T_1$ states,[13] respectively. Important features in this figure are as follows: The energy curves of the ground state and the ^2E state are parallel to each other because of the same electron configuration associated with them. However, the minimum positions of the $^4T_2$ and $^4T_1$ states are displaced from the minimum of the ground state, and the curvatures of these curves are not necessarily equal to that of the ground state. This fact can be ascribed to the electron configurations associated with the excited quartet states being different from that of the ground state. The displacement of the energy minima of the excited quartet states is evidenced by the observed broadness of the absorption bandwidths (Franck-Condon principle). In such circumstances, the energy curves of the excited quartet states cross those of the excited doublet and the ground state, while the energy curve of the doublet state does not cross the ground energy curve.

According to the general theory of nonradiative processes worked out by several people,[16] excited electrons in the quartet states may reach the excited doublet state or the ground state through these cross points nonradiatively at high temperatures, and, at low temperatures, they may tunnel activation barriers. These processes are more clearly illustrated in Fig. 6. At high temperatures, the activation energy, $\epsilon^* - \epsilon_0$, appears in the nonradiative process (arrow A in Fig. 6) from the upper state to the lower state. At low temperatures, the tunneling process indicated by arrows B in Fig. 6 may exceed the activation process. Then, the nonradiative transition probability is determined by the width of the activation wall instead of by the activation energy. If we assume the energy curves to be parabolas with the same curvature, the probability of tunneling is sensitive to the factor,

$$[\gamma \exp(1 - \gamma/2)/2]^{\epsilon_0/\hbar\omega},$$

where γ is defined in such a way that the vertical transition energy from the lower state minimum to the upper state is given by $(1 + \gamma/2)\ \epsilon_0$, and $\hbar\omega$ is a quantum energy of the phonon active in this process. When γ approaches 2, the wall width approaches zero, and a large probability of tunneling is expected.

According to the recent experiment by Kuwabara and Misu,[17] the quantum efficiency of the ruby fluo-

rescence, when it is excited by light in the green or blue band, is as high as ~0.5 at liquid nitrogen temperature, and the efficiency still increases at this temperature as temperature decreases. A high quantum efficiency is also observed when the fluorescence is excited by light of the same frequency as that of the fluorescence, but, in this case, the temperature dependence of the quantum efficiency is different from that in the former case: when the temperature is decreased, the initially increasing quantum efficiency is saturated at ~500°K, and the flat curve extends to the region of low temperatures beyond room temperature. The observed temperature dependence seems to show that the activation process from the excited quartet state to the ground state is still working at liquid nitrogen temperature, but the activation process from the doublet state to the ground state is not. This experimental fact is comprehensible from Fig. 5. The observed high quantum efficiency indicates the difficulty of obtaining nonradiative decays to the ground state. It is further considered that the high quantum efficiency is due to the rapid nonradiative decay of electrons in the excited quartet states to the doublet state,[18] and also to the almost purely radiative decay from the doublet to the ground state.[19] In order to examine the possibility of the tunneling process, it is desirable to extend the experiments to lower temperatures. For the nonradiative decay between the quartet and doublet states, spin-orbit interaction should also be taken into account, of course.

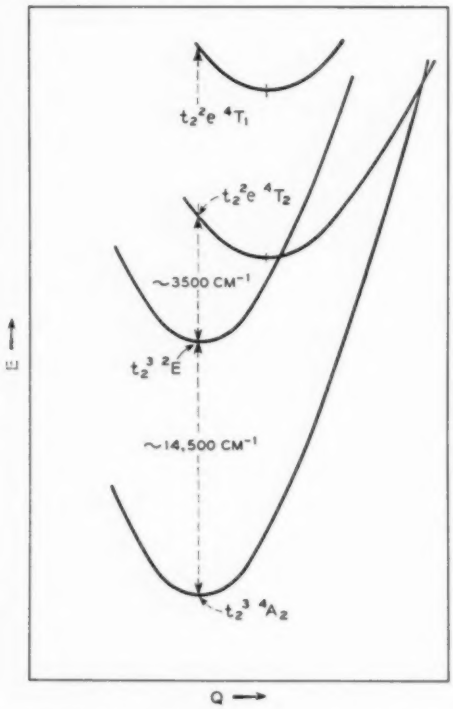


Fig. 5. The schematic energy diagram of Cr^{3+} in cubic field illustrated in one-dimensional configuration coordinate.

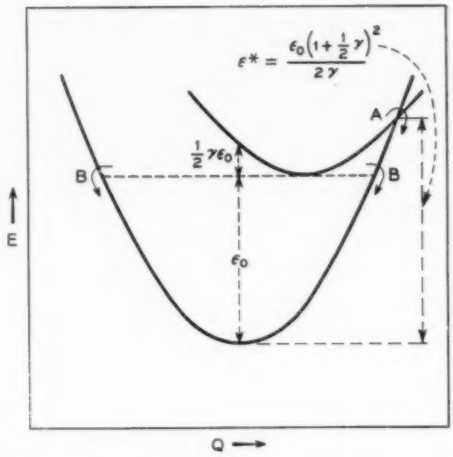


Fig. 6. A schematic energy diagram which shows activation and tunneling processes from the upper state. (After Kubo and Toyozawa.[16])

A similar argument may also be applied to the case of divalent rare earth ions in crystals, when the displaced energy curve is identified with the state involving the 5*d* orbital, and the undisplaced one is identified with the state which is constructed purely from the 4 orbitals.

V. Actinide Group Ions

In view of the recent success of Sorokin and Stevenson[20] in observing maser oscillation in $CaF_2:U^{3+}$ crystals, it would be desirable to extend our discussion to actinide group ions in crystals. It is generally admitted that the ground states of highly ionized actinide group elements have the electron configuration $5f^n$, whereas the 6*d* and/or 7*s* orbitals are partly or completely filled in the ground states of the neutral atoms. Suggested electron configurations for neutral actinide group elements by Seaborg[21] are as given in Table I.

The optical spectra of actinide group ions in crystals or aqueous solutions show a large amount of fine structure around the visible region somewhat similar to the spectra of rare earth ions in crystals.[22,23] Fluorescence has been reported from Am^{3+},[24] Pu^{3+},[25] U^{3+}, Np^{3+}, Cm^{3+},[26] in $LaCl_3$ crystals, and U^{3+} in CaF_2, SrF_2, BaF_2 crystals.[27] Detailed measurements of the line widths and intensities, however, seem not to have been reported yet. Some efforts have been exerted to explain these spectra,[28,29] but our present knowledge of these elements, especially on the theo-

Table I

Atomic no.	Elements	Electron configurations (Rn) +
89	Actinium	$6d7s^2$
90	Thorium	$6d^27s^2$ (or $5f6d7s^2$)
91	Protactinium	$5f^26d7s^2$ (or $5f6d^27s^2$)
92	Uranium	$5f^36d7s^2$
93	Neptunium	$5f^57s^2$ (or $5f^46d7s^2$)
94	Plutonium	$5f^67s^2$ (or $5f^56d7s^2$)
95	Americium	$5f^77s^2$
96	Curium	$5f^76d7s^2$
97	Berkelium	$5f^97s^2$
98	Californium	$5f^{10}7s^2$

ertical side, is rather poor and a detailed discussion would better be reserved for the future.

The $5f$ orbital is likely to have a larger radius than that of the $4f$ orbital and the shielding by outer electrons, $6s$ and $6p$, is less complete, so that the coupling of the $5f$ electrons with a lattice would be stronger than that of the $4f$ electrons. This enables us to expect fairly strong absorptions as in the case of transition metal ions in crystals. Galkin and Feofilov[27] have reported the strong colorations of the crystals involving uranium compared with the crystals containing the same amount of neodymium. This is a favorable situation for the optical maser application.

The author would like to express his sincere thanks to J. R. Haynes, D. L. Wood, C. G. B. Garrett, W. Kaiser, and D. M. Dodd for permission to use the figures and for helpful discussions, to G. Kuwabara and A. Misu for showing him the unpublished data, and to A. L. Schawlow, W. S. Boyle, and D. G. Thomas for illuminating discussions.

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OSA Group Flight to ICO Munich Meeting August—see page A18 for application blank.

Applied Optics BOOKS

Books for review should be submitted to the Managing Editor, APPLIED OPTICS, 1155 16th St., N.W., Washington 6, D.C.

ABC der Optik. By KARL MÜTZE, LEONHARD FOITZIK, WOLFGANG KRUG, AND GÜNTER SCHREIBER. Verlag Werner Dausien, Hanau/Main, 1961. 963 pp. + 28 plates. DM 37.40 ($8.90).

It is natural for any group of people with mutual interests to develop its own jargon which may be nearly unintelligible to the uninitiated. Workers in the field of optics are no exception as a quick glance at the first issue of *Applied Optics* readily shows. Thus a nonspecialist who wishes to read about some particular aspect of the subject may find an encyclopedia such as the *ABC der Optik* useful. This book describes many of the terms and expressions which occur in the German literature on optics. Classically, optics is divided into biological optics—the study of the visual process, and physical optics—the study of the nature of light and its interaction with matter. Both branches are covered in this book. However, physical optics shows a tendency to embrace an everwidening region of the electromagnetic spectrum, and the authors must have had many difficult decisions in deciding what should or should not be included. Thus there are numerous entries concerning the x-ray, ultraviolet, and infrared regions of the spectrum but none under radar, or radiowellen.

About half of the 10,000 entries consist of synonyms which are cross-referenced to other entries. The remainder range from one or two lines to several pages in length. Although analytical expressions and derivations are occasionally included, the articles are mainly descriptive with numerous line and halftone illustrations. Tabulations of optical properties of materials have been avoided since they are available elsewhere. Several excellent concise articles discuss the fundamental theories of geometrical, physical, and physiological optics. Among other topics discussed are various atmospheric optical phenomena, e.g., mirages, halos, rainbows, and scattering. Some of these effects are illustrated in color at the end of the book; one can also find the Braille alphabet and the dimensions of the standard sizes of photographic film and plates. On page 326 there is a diagram showing the variations in color of the Atlantic Ocean. However, there are no entries under some recently coined terms such as maser or laser.

This book will be a useful addition to many libraries since many of the entries are not listed in other reference books. Unfortunately its use will be restricted in this country since it is written in German, but its existence may stimulate the production of a similar reference work in English.

J. H. SHAW

Editor's Note: It may be of some interest to point out some remarks made in the Introduction of this book by Prof. Paul Görlich of Jena, who is a Director at the Institute for Optics and Spectroscopy in Berlin-Adlershof. "*Since the idea of assembling such an ABC of Optics had its origin in this Institute* [which is located in the East Sector of Berlin], *it is no wonder that nearly half of the entries are the work of scientific members of this institute. However, many of the other contributions are from West German Institutes* [Munich, Freiburg, and West-Berlin, for example] *so that it can be considered an all-German* [gesamtdeutsche] *effort.*" Your Editor visited Prof. Krug and Dr. Schreiber while this work was being prepared and can verify that assembling 10,000 entries and 1600 illustrations into a handbook is a major operation. It is interesting to note that they prefer "infrarot" to "ultrarot" (for "infrared"), so that the abbreviations IR and UV can be considered internationalized. The Editor would like also to state that he has found this particular book perhaps the most useful reference on his optics bookshelf in the course of editing articles for *Applied Optics* over the past year. Articles come in concerning technical subjects in which the editor is not trained, and European contributions come in using terms with which we are not familiar. We are happy to state that this very useful book has come to our aid many times.

We believe Hilger, Watt, Ltd, are planning to publish a translated edition.

Refractometry and Chemical Structure. By S. S. BATSANOV. Moscow Univ. Press, 1959. Translated by P. P. SUTTON. Consultants Bureau Enterprises, New York, 1961. 250 pp. $9.75

Intended as a monograph on the use of refractometry in solving problems of chemical structure, this text addresses itself mainly to the practitioner in that field. Discussion of experimental studies, usually presented in historical perspective, and their interpretation, is stressed rather than a rigorous exposition of the theoretical foundations or the physics of the experimental technique.

The brief introductory citation of a number of formulas for refraction at optical frequencies is followed by a critical comparison and detailed tabulation of the various systems of atomic refractions (notably those due to Eisenlohr and to Vogel), including a treatment of optical exaltation and the dependence of the atomic refraction on the valence state of the atom. A discussion is then given of bond refractions, with a tabulation of Vogel's system based on the method of Denbigh, and of ionic refractions, with a tabulation of the latter according to Wasastjerna and Fajans. A detailed comparison of experimental and semiempirical calculations of ionic refractions in crystals is made, while *a priori* calculations of ionic refractions and optical exaltation are briefly commented upon. In conjunction with a discussion of electronegativity, tables of atomic and ionic radii calculated as a function of the degree of ionization are provided. In the treatment of the effect of the state of aggregation on the molecular refraction, a discussion of the internal field problem is conspicuous by its absence. The chapter closes with an extensive commentary and a tabulation of experimental and calculated molecular refractions of gases, liquids, and crystals, including an error analysis.

A number of special topics are treated in considerable detail, in most instances attended by copious examples of arithmetical calculations. These subjects are introduced by a penetrating survey of refractometric work on inorganic and organic hydrogen-bonded systems. Subsequently, a review of the refractometry of solutions is presented, wherein the discussion of the quantitative theory of Böttcher for the optical refraction of electrolyte mixtures and the qualitative considerations of Fajans appears to underscore the author's emphasis on empiricism. An application of refractometric methods to the determination of the structural formulas of silicates, and to the study of organic substances and inorganic complexes is given. In this connection and others, the problem of the dispersion of the index of refraction and its relation to the transitions moments and frequencies of molecular transitions is touched upon, but is at no point given a definitive exposition. The main body of the text concludes with an interesting account of the calculation of interatomic distances in crystalline substances, and the investigation, by refractometric methods, of the trans-effect in complexes.

An appendix is provided which gives a table of values of the Lorenz–Lorentz function for $n = 1.3$ to $n = 2.0$, in intervals of

continued on page 334

Threshold Condition of Masers for Higher Frequencies

Koichi Shimoda

After a brief discussion on the quality factor of a parallel-plate interferometer, threshold conditions of oscillation for a beam maser, a solid-state maser, and a gas maser are calculated from a unified theory. Operation of a gas maser on the line broadened by both collision and the Doppler effect is discussed. The rate of producing population inversion is calculated in terms of gas pressure, quantum efficiency, saturation parameter, and the intensity of excitation. Finally, the optimum condition is discussed.

I. Introduction

Interest in optical and infrared masers is increasing rapidly after successful operations of solid-state masers and more recently of a gas maser.[1] Basic considerations on high-frequency masers have been discussed by Schawlow and Townes.[2] The aim of this paper is to develop a unified theory[3] of various types of masers and to discuss optimum operating conditions[4] in a general way.

The ordinary operation of a maser requires that atoms or molecules in a resonator should have the distribution corresponding to a negative temperature or a population inversion between two states. Of course there are a few types of masers which do not require population inversion. An example of this type, using a multiple quantum transition in the conventional microwave range, has been studied,[5] but the application of such methods to higher frequencies is not included in the following discussion.

II. Parallel-Plate Resonator

In the absence of loss between the plates, the quality factor Q of a parallel-plate interferometer with a separation d is calculated from the power reflection coefficient R of each plate. The stored energy in the resonator decays according to the expression $W = W_0 \exp(-\omega_0 t/Q)$, which must be equal to the reflection loss for $t = d/c$:

$$R = \exp\left(-\frac{\omega_0}{Q}\frac{d}{c}\right) \simeq 1 - \frac{\omega_0}{Q}\frac{d}{c},$$

where $\omega_0/2\pi = c/\lambda$ is the frequency of oscillation. Then the quality factor can be expressed by

$$Q_0 = \frac{2\pi d}{\lambda(1-R)}. \tag{1}$$

For example, for $\lambda = 10^{-4}$ cm, $R = 0.99$, and $d = 10$ cm, $Q_0 = 6.3 \times 10^7$.

The loss of power through the side openings may be evaluated from the diffraction of reflected light. According to the standard theory of diffraction, the angle of diffraction θ from the edge of the plate can be approximately given by

$$d(1-\cos\theta) \approx \frac{\lambda}{2\pi}, \text{ or } \theta = \sqrt{\frac{\lambda}{\pi d}}. \tag{2}$$

The loss of power P_d by diffraction for reflectors in the form of square plates of side dimension L or circular plates of diameter L can be expressed by the increase of $1/Q$ as

$$\frac{1}{Q_d} = \frac{P_d}{\omega_0 W} \approx \frac{2\lambda}{\pi L}\sqrt{\frac{\lambda}{\pi d}}.$$

Taking $L = 1$ cm, $d = 10$ cm, $\lambda = 10^{-4}$ cm, the above equation gives $Q_d \approx 9 \times 10^6$, which is considerably smaller than Q_0 from Eq. (1).

However, the above estimate cannot be applied to the resonator of a high-frequency maser for the following reason. If the coherent length of radiation is much longer than $d/(1-R)$, the homogeneous distribution of the light amplitude over the surface of the reflector does not exist. The distribution must have a maximum at the center and decrease near the edges. When the amplitude near the edge is small, the diffraction given by Eq. (2) is reduced since it arises from the dominant interference of components coming from a narrow belt within $(\lambda d/\pi)^{1/2}$ from the edge of the plates.

If the field distribution on a square reflector has a form $\sin(n\pi x/L)\cdot\sin(m\pi y/L)$, where x and y extend from 0 to L, the spill-off power from the edges due to

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diffraction is expressed by

$$\frac{1}{Q_d} \simeq \frac{\lambda^2}{4\pi L^2}(n+m). \tag{3}$$

It should be noted that a mode with $n = 1$ and $m = 0$ exists in a rectangular cavity but any similar mode in a parallel-plate resonator does not exist. The lowest mode has a similar field distribution to the case $m = n = 1$, which gives the diffraction loss as

$$\frac{1}{Q_d} \approx \frac{\lambda^2}{2\pi L^2}. \tag{4}$$

III. Threshold Condition for the Maser

The stored energy W of the high-frequency field in the resonator drops by an amount

$$\Delta P = \frac{\omega_0 W}{Q} = \frac{\nu_0}{4Q} E^2 V \tag{5}$$

in unit time, where E^2 is the space average of the field intensity squared, V is the effective volume of the resonator, and $W = (E^2/8\pi)V$.

The power delivered by atoms or molecules in a weak field of $E\cos\omega_0 t$ is calculated by a well-known method.[6] The result for the case when the oscillation frequency ν_0 is close to the resonant frequency of atoms is given by[3]

$$\Delta P_e = nh\nu_0 \left(\frac{E\bar{\mu}}{2h}\right)^2 \left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av}, \tag{6}$$

where n is the number of excited molecules supplied in unit time, and t is the time of interaction with the radiation (between successive collisions in a gaseous case). The average in Eq. (6) is taken over the distribution of the resonant frequency of each atom $\nu = \omega/2\pi$, where $\delta = (\omega - \omega_0)t/2$, and over the distribution of t.

The component of the dipole matrix element $\bar{\mu}$ along the direction of the field is given by $\bar{\mu}^2 = {}^1/_3\,\mu^2$. Then the threshold condition of maser oscillation is obtained from $\Delta P_e \geq \Delta P$. The threshold rate of supply of atoms in the upper level is

$$n_{th} = \frac{3hV}{4\pi^2\mu^2 Q} \left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av}^{-1}. \tag{7}$$

A. Beam-Type Maser

A beam of atoms or molecules is passed nearly parallel to the surface of a parallel-plate resonator in order to reduce the Doppler broadening of the line. When an atom in the beam has a transverse velocity v_t normal to the plate, the Doppler effect gives a frequency shift of $v_t\nu_0/c$ and δ can be expressed as

$$\delta = \frac{\pi\nu_0 v_t l}{c} = \pi \frac{v_t}{v} \frac{L}{\lambda},$$

where L is the length of the resonator and v is the longitudinal velocity. Hence the line is narrowed in proportion to the directivity of the beam.

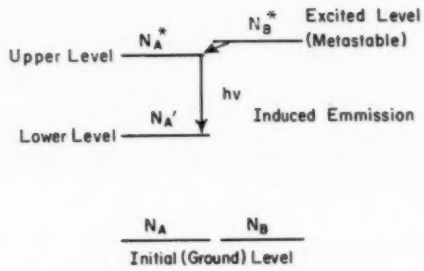

Fig. 1. Energy levels of atoms A and B.

Beam-type masers can be used when the probability of spontaneous emission $1/\tau_s$ is negligible or $\tau_s \gg L/v$ so that $t = L/v$. When $|\delta| \ll \pi$, an approximation $\sin^2\delta/\delta^2 \approx 1$ can be used. When $|\delta| \gg \pi$, one obtains

$$\left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av} \approx \frac{L\lambda}{2v\langle v_t\rangle},$$

where $\langle v_t\rangle$ is the average of the transverse velocity. Then the threshold flow of atoms in the upper state may be given by[8]

$$n_{th} = \frac{3hV}{2\pi^2\mu^2 Q} \cdot \frac{v}{L}\left(\frac{v}{2L} + \frac{\langle v_t\rangle}{\lambda}\right). \tag{8}$$

B. Solid-State Maser

The Doppler broadening is negligible in a solid-state maser because the frequency of thermal vibration is much higher than the relaxation frequency so that the Doppler shift averages zero. In the case of an ideal solid, one may assume $\delta = 0$ and the half half-width of the line is $\Delta\nu = 1/(2\pi\tau)$. Then one obtains

$$\left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av} = \langle t^2\rangle_{av} = 2\tau^2.$$

The threshold rate of excitation is therefore given by

$$n_{th} = \frac{3hV}{8\pi^2\mu^2 Q\tau^2}, \tag{9}$$

and the necessary number of excess atoms in the upper state is

$$N_{th} = n_{th}\tau = \frac{3hV\Delta\nu}{4\pi\mu^2 Q}. \tag{10}$$

However, in an actual crystal, atoms spread over a range of frequencies, due to the internal stress and the local field in the crystal. On the plausible assumption that the distribution of the frequency of each atom is given by a Gaussian distribution, the calculation can be carried out in the same way as for the gas maser which is described below.

The transverse relaxation time T_2 in a solid and the Doppler broadening in a gas are responsible for dephas-

ing the high-frequency polarization of atoms or molecules. The longitudinal relaxation time T_1 in a solid and the time interval of strong collisions in a gas depopulate the upper level.

C. Gas Maser

The spread of the frequencies of the atoms in a solid can be treated as the Doppler broadening of the line of atoms in a gas. In either case the relaxation of the population of levels can be expressed by $\exp(-t/\tau)$. The distribution of the velocity component v along the direction perpendicular to the surface of the wave is proportional to $\exp(-v^2/\alpha^2)$, where $\alpha = (2kT/M)^{1/2}$ is the most probable velocity.

The threshold condition for masers in which the line is broadened both by the Doppler effect and by collisions is discussed in the following: The collision is assumed to be strong. The weak collision which does not thermalize the levels but varies the phase of the radiation is neglected here for simplicity of discussion.

The factor in Eq. (6) averaged over-all atoms in the gas can be written as

$$\left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av} = \frac{2}{\sqrt{\pi}\alpha\tau} \int_0^\infty \int_0^\infty \frac{\sin^2(\pi\nu_0 x t/c)}{(\pi\nu_0 y/c)^2} e^{-x^2/\alpha^2} e^{-t/\tau} dy dt. \tag{11}$$

After integration with respect to t, Eq. (11) may be rewritten as[4]

$$\left\langle \frac{\sin^2\delta}{\delta^2} t^2 \right\rangle_{av} = \frac{4\tau^2 p^2}{\sqrt{\pi}} \int_0^\infty \frac{e^{-x_2}}{p^2 + x^2} dx$$

$$= 4\tau^2 p\, e^{p^2} \int_p^\infty e^{-x^2} dx, \tag{12}$$

where

$$p = \frac{c}{2\pi\alpha\nu_0\tau}$$

is proportional to the gas pressure.

Then, the threshold rate of supplying atoms in the upper stage is obtained by substituting Eq. (12) into Eq. (7) as

$$n_{th} = \frac{3hV}{2\sqrt{2}\mu^2 Q} \left(\frac{\alpha\nu_0}{c}\right)^2 \frac{p\exp(-p^2)}{1 - \Phi(p)}, \tag{13}$$

where

$$\Phi(p) = \frac{2}{\sqrt{\pi}} \int_0^p e^{-x^2} dx$$

is the error integral. Asymptotic solutions for cases of high pressure and of low pressure are easily found.[4] It is evident, however, that the optimum operation of a maser takes place under an intermediate pressure.

IV. Rate of Excitation

There are a variety of methods of producing population inversion. Typical methods are state-separation of atoms or molecules in the beam, optical pumping, collision excitation of the second kind by excited atoms, chemical reaction, etc. Depopulation of the lower state plays an important role in some cases (e.g., the beam-type maser), while in most other cases the selective excitation of atoms to a particular upper level is essential. In such cases the rate of excitation can be expressed in the common form

$$n_{ex} = \frac{\gamma I}{1 + \beta I p^{-2}}, \tag{14}$$

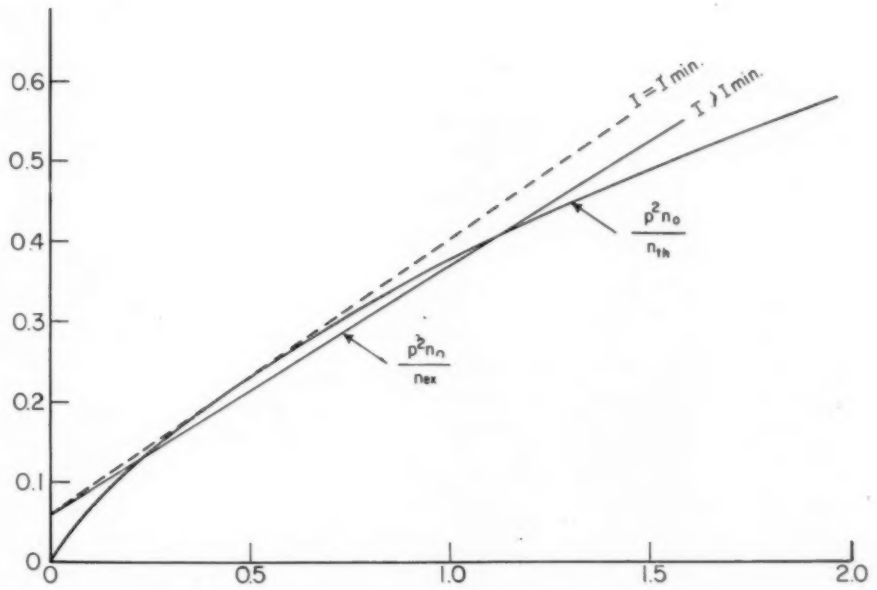

Fig. 2. Graphical representation of p^2n_0/n_{th} and p^2n_0/n_{ex} versus p^2.

where I is the number of quanta of the input power for excitation, γ is the quantum efficiency, and β is a saturation parameter.

It is known that the rate of excitation by absorption of a coherent electromagnetic radiation is given in the form of Eq. (14).[7] It is shown here that the same expression is applicable to the excitation by collision of the second kind or by chemical reaction. Consider that the working atom A is excited by the other energetic particle B, and the increase of the excited atom A is written by

$$\frac{dN_A^*}{dt} = N_A N_B^* w_e - N_A^* N_B w_d - \frac{N_A^*}{\tau_A}, \qquad (15)$$

where w_e and w_d are the probabilities of excitation and de-excitation respectively, and τ_a is the relaxation time of the atom A. For effective performance of the maser the case of $w_e \gg w_d$ is desired, so that the term with w_d in Eq. (15) may be neglected. If it is not negligible, by assuming that N_B is proportional to the gas pressure, one may write

$$N_B w_d = \frac{1}{\tau'_A} \quad \text{and} \quad \frac{1}{\tau} = \frac{1}{\tau_A} + \frac{1}{\tau'_A}.$$

Then the rate of exciting the atom A to its upper state is given by

$$n_{ex} = N_A N_B^* w_e = \frac{N_A^*}{\tau}. \qquad (16)$$

The change of population of the initial level (usually the ground level) of the atom A is given by

$$\frac{dN_A}{dt} = -N_A N_B^* w_e + \frac{N_A^{(0)} - N_A}{\tau}, \qquad (17)$$

where $N_A^{(0)}$ is the population of the atom A in the absence of excitation. If the mean life of B* is written as τ_B, the number of quanta of the net input power for excitation is $I = N_B^*/\tau_B$. Then the solution of Eq. (17) for the stationary state in the presence of excitation is substituted into Eq. (16) to obtain the rate of excitation

$$n_{ex} = N_A w_e I \tau_B = \frac{N_A^{(0)} w_e I \tau_B}{1 + w_e I \tau_B \tau}. \qquad (18)$$

In some cases it is reasonable to assume that τ_B is proportional to τ, and $N_A^{(0)}$ is proportional to τ^{-1}. Then Eq. (18) is reduced to Eq. (14). However, the above assumption does not hold when the relaxation time τ of atom A is primarily determined by the spontaneous emission which is of course independent of the collision.

V. Optimum Pressure for Maser

Now the condition for the maser-type amplification or oscillation is obtained from Eqs. (13) and (14) or (18). It may be expressed as the supplying of a sufficient amount of excess population of the upper state over the lower state to which the atom makes a transition through the process of induced emission.

For simplicity of discussion, it may be assumed that the excitation to the lower state occurs in proportion to that to the upper state. The thermal excitation is considered to be small in the high-frequency maser.† Then the effective rate of excitation is written as $(1 - r)n_{ex}$ and the condition is expressed by

$$(1 - r)n_{ex} > n_{th}. \qquad (19)$$

This condition can be rewritten from Eqs. (13) and (14) in the form

$$(1 - r)\ \frac{n_0}{\gamma}\left(\beta + \frac{p^2}{I}\right) < p \exp(p^2)[1 - \Phi(p)], \qquad (20)$$

where n_0 is a constant given by

$$n_0 = \frac{3hV}{2\sqrt{2}\mu^2 Q}\left(\frac{\alpha\nu_0}{c}\right)^2. \qquad (21)$$

The right-hand term of (20) is $p^2 n_0/n_{th}$, and is shown graphically in Fig. 2 as a function of p^2. The left-hand term, $p^2 n_0/n_{ex}$, is shown by a straight line. The slope of the line is $(1 - r)\ n_0/\gamma I$ and the intercept of the ordinate is equal to $(1 - r)n_0\ \beta/\gamma$. Maser oscillation occurs in the region where the straight line lies below the curve. The minimum input power of excitation is of course given by a tangent which is shown by a broken line in Fig. 2.

Discussions of the performance for particular cases are here, but it can be concluded from Fig. 2 that when $(1-r)\cdot n_0\ \beta/\gamma$ is small, the maser can be operated at a small input power and at a low pressure. As the value of $(1 - r)n_0\ \beta/\gamma$ increases, larger gas pressure is required and the minimum input power increases. From Eqs. (18) and (21) the magnitude of the intercept is given by

$$(1 - r)\ \frac{n_0\beta}{\gamma} = \frac{3hV}{8\pi^{5/2}\mu^2 Q C_A},$$

where $C_A = N_A^{(0)}\tau_A$. Since this is independent of w_e, the optimum pressure does not depend on w_e. The slope is

$$(1 - r)\ \frac{n_0\beta}{\gamma I} = \frac{n_0\tau}{w_e C_A \tau_B I},$$

which depends on w_e. Hence the required exciting power varies in proportion to w_e^{-1}.

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† If thermal excitation to the lower state is important, the effective rate of excitation n_{ex} necessary for the maser is given by

$$n_{ex}\tau - N'_A > n_{th}\tau,$$

where N'_A is the population of the lower state.

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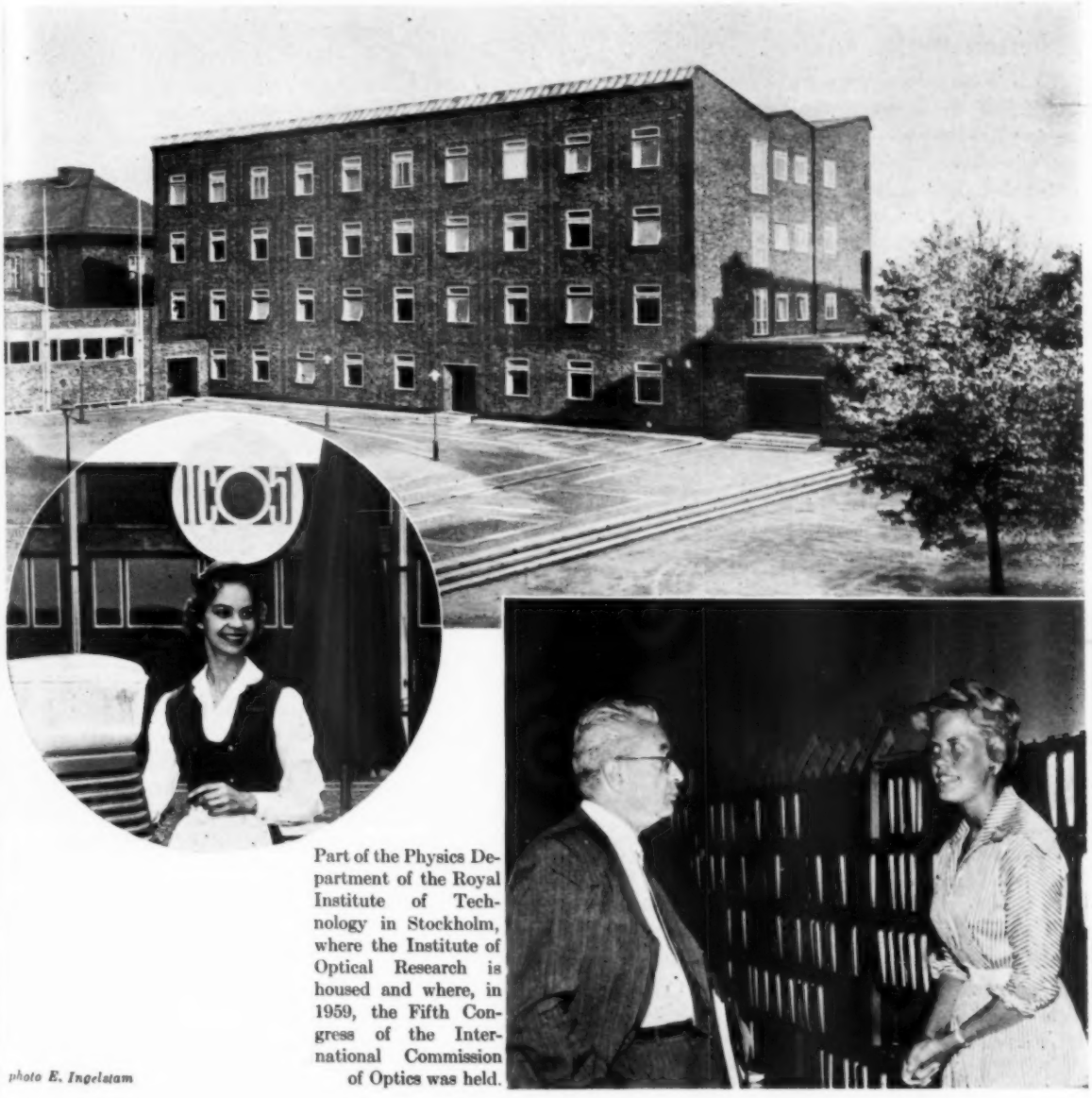

Part of the Physics Department of the Royal Institute of Technology in Stockholm, where the Institute of Optical Research is housed and where, in 1959, the Fifth Congress of the International Commission of Optics was held.

photo E. Ingelstam

Optics in Germany

A. Lohmann

This article presents a short survey of the people and organizations active in optics research in Germany.

I. Organization

To be well informed about optics in Germany one should join (for 75 cents) the DGAO (German Society for Applied Optics). A program and an extended report of the annual meetings which take place usually in the week following Whitsuntide are sent to members. In this report, published as a double issue of the journal *Optik* (the joint publication of DGAO and of the German Society for Electron Microscopy), are listed the addresses of some 300 individual DGAO members and of the corporation members (most of the German optical companies are represented).[1] The president of the DGAO is Professor Dr. G. Hansen from Carl Zeiss, the vice-president, Professor Dr. E. Lau from the Institute of Optics and Spectroscopy in Berlin-Adlershof, and treasurer-secretary, Professor Dr. H. Volkmann (Heidenheim/Brenz, Waechterstr. 1). DGAO cooperates with the Association of German Physical Societies (VDPhG), and has good contacts in the neighboring countries; many foreign scientists attend its meetings. Most of the German optics papers are published in *Optik*, *Zeitschrift für Physik*, and in *Optica Acta*.

The German National Committee for Optics is headed by Professor Dr. G. Cario of the Technische Hochschule, Braunschweig. The secretary, who is organizing the Sixth Conference of the International Commission of Optics to be held in Munich (August 19–26, 1962), is Professor Dr. Dr. H. Schober of the Institut für Medizinische Optik der Universität Muenchen.

The German National Research Council (DFG) in Bonn has a special committee for applied optics, which these last two years has been classified an "urgent topic." A Colloquium on Optics and Spectroscopy covering all wavelengths is held every second year in Jena, and the proceedings are published by the Akademie-Verlag in East Berlin.

II. Optical Research Institutions

The oldest optical research institute (Optisches Institut der Technischen Universitat Berlin-Charlottenburg) was founded about 40 years ago by Professor Weidert, formerly a lens designer with Goertz. Even today, under the direction of Professor H. Slevogt, lens design takes pride of place, but now the field has expanded and includes all theoretical and experimental aspects of image formation. One of their test benches, which includes an analogue computer, displays simultaneously on a CRT the optical transfer function, the line spread function, the edge image, and one more measure which I believe is the one-dimensional analogue to the encircled energy (for this quantity I would propose the name "STRAUBEL measure," since Straubel used this parameter nearly 70 years ago). The institute publishes its own *Mitteilungen*.

The only German optical research institute with more than three permanent professional members is the Institute of Optics and Spectroscopy, located in East Berlin. Professor Lau, the vice president of DGAO, founded it about 15 years ago. His major contribution was perhaps the development of "equidensitometry" (lines of equal photographic density) as a useful tool for measurements in many scientific and technical applications. Related to this, which has been fully described elsewhere,[2] is the "Schwaerzungsplastik" (thickness deformation of photographic emulsions according to grain concentration). Based on two-beam interferometry, it permits evaluation of densities up to 5. Much effort has gone into developing new interference microscopes and proper techniques of evaluation (dupligramm = moiré of two interferograms). This Institute is also studying problems in atmospheric optics, physiological optics, and spectroscopy.

For about 5 years there has been an institute for

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medical optics at the University of Munich, where special attention is paid to the information aspects of vision. Reliable measurements of the eye lens transfer function have been performed and other experiments concerning the statistical properties of photographic images. The director, Professor Schober, has written the standard work in the German language on physiological optics.

At Jena University there is an optical institute (Professor Kuehne) which may have the longest tradition. Unfortunately, I have never visited this institute, so I cannot say more than that their efforts are connected with metrological problems in the nearby optical factories.*

A fairly new optical institute is the one at the Technische Hochschule in Stuttgart (Professor Schulze). The curriculum is supported by Professor Hansen and Professor Koehler from Carl Zeiss, and I believe the research is concerned with instrumentation.

III. Research in the Optical Industry

It was difficult to give a succinct survey of optical research within the optical institutes, and it seems impossible to me to give proper credit to the research activities in the German optical industry. At the DGAO meetings there are many papers on lens design, image quality, contrast transfer, interference, spectral apparatus, astronomical optics, photometry, centering of lens elements, stereo vision, and other topics. But these papers from industrial workers are presumably only a small part of the research results obtained. I think this is partially due to the scarcity (when compared with the U.S.A.) of government-sponsored contracts. To a foreigner, it appears that government contracts not only stimulate the industrial research itself, but also its publication.

Obviously the best way to obtain detailed information about the optical activities in German industry is to read *Optik*, to ask the industrial companies for descriptive material, or preferably to visit them. Let me conclude this section with an example which illustrates active participation of the industrial laboratories in modern research problems: All companies which I visited within the past few years are able to calculate and to measure the contrast transfer functions of lens systems. In most cases the principles used were not simply copies from the literature, but were based upon original ideas.

IV. Other Optical Research Facilities

There are many research institutions, not solely concerned with optics, having small groups working in this field. Most of these are part of university physics departments:

Professor Boersch (*TU West Berlin*) is mainly interested in electron optics, particularly in interferometers and the Bohn-Aharonov effect. For this purpose his group has performed model experiments with visible light, e.g., using Zernike's coherent background.

Professor Cario's group (*TH Braunschweig*) includes W. Lukosz, the writer, and, recently, E. Menzel. The calculation, the measurement, and possible improvements to the optical transfer function have been investigated. Other areas studied are spectral apparatus, interference microscopy, optical surface quality, and optical feedback systems.

Professor Czerny (*Universität Frankfurt*) is well known for his many contributions to infrared optics. Professor Genzel, who is mentioned below, was formerly his co-worker.

Professor Focke (*Universität Leipzig*) has made mathematical contributions to image formation and lens design (method of stationary phase).

Professor von Fragstein (*Universität Saarbrucken*) is working in the field of physical optics, e.g., thin layers and Fresnel zone plates.

Professor Frieser (*TH Muenchen*) is one of the pioneers of the photographic contrast transfer. In addition to his photochemical activities, he studies photographic noise.

Professor Genzel (*Universität Freiburg*) has a grating with variable blaze angle and another with variable groove depth. He uses these gratings for infrared spectrometric studies.

Professor Haken and Dr. Kaiser (*TH Stuttgart*) are working on laser problems. Dr. Kaiser is on leave of absence from Bell Telephone Laboratories.

Professor Kroebel (*Universität Kiel*) studies the parameters which influence the subjective quality of TV images.

Professor Lassen (*FU West Berlin*) is interested in spectral apparatus and waveguide theory applied to multiple-beam interferences.

Professor Menzel (*TH Braunschweig*) recently published a work on the theory of image formation, coherence, and on image recording upon rubber elastic surfaces.

Professor Picht (*PH Potsdam*) well known from his books on geometrical optics, test methods, electron optics, and other topics, has contributed to many fields such as aberration theory, total reflection, wave mechanics, etc.

Professor Steinbuch (*TH Karlsruhe*) is active in the field of optical character recognition.

Professor Stockmann (*TH Karlsruhe*) works in solid-state physics applied to optoelectronics (logic circuits consisting of photoconductors and electroluminescent elements; image intensifier).

* Professor Görlich has prepared a more detailed survey of optics in the DDR for a future issue—Ed.

Professor Wolter (Universität Marburg) wrote a series of articles on information theory in optics. Experiments with Schlieren systems and for contrast transfer investigations have been performed. The curriculum in optics at Marburg University and at the nearby Giessen University is supplemented by members of Leitz: Dr. Claussen, Professor Franke, Professor Marx, Professor Roesch.

Finally, there are some research facilities which should be mentioned which fit neither into the "optical industry" nor into the "university" heading. Almost every optical specialty is covered by the optical department in the PTB (the German equivalent of the National Bureau of Standards or the British National Physical Laboratory) at Braunschweig. Professor Korte, the head of the department is mainly concerned with photometry. Dr. Rosenbauer and Dr. Rosenbruch have three different devices for measuring the contrast transfer function. Dr. Duehmke designs interferometers for the measurement of length while Dr. Engelhard develops light sources for the same purpose. Dr. Buennagel has, as a flatness norm, a mercury mirror which is not sensitive to vibration.

The joint research institute of the German broadcasting companies IRT has an optical laboratory in Hamburg. Dr. Below has worked on lens testing, image quality, and color problems.

In Dortmund there is a new Institute for Spectroscopy and Spectrochemistry. It performs applied research under the direction of Professor Kaiser.

Writing this report has allowed no time for checking the statements in it; the contents is based only upon my memory. Therefore I hope my fellow physicists at home will forgive me if I do not give proper mention to their work. Since this review may be incomplete, the best suggestion I can offer for better information is to visit us personally. We hope you will do that while you are in Germany for the ICO Conference in Munich.

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Papers to appear in subsequent issues

We have had so many papers submitted for publication since *Applied Optics* was announced last year that we have already built up a backlog which is as embarrassing for a new publication as it is a demonstration of the need for this journal. We are doing our best to publish papers as quickly as we can by bringing out bigger issues than had originally been intended this year, and becoming a monthly in 1963. The Editors wish to express their sincere appreciation to all contributors who have thus demonstrated their faith in *Applied Optics*.

Inspecting Infrared Optical Materials and Systems by means of the Evaporograph—*McDaniel and DiMattia*
Overlapping Monoculars: An Ultrawide Field Viewing System—*Shenker et al.*
High-Speed Rotating-Mirror Framing Camera—*Davis*
Luminescent Processes and Decay Laws in Crystalline Materials—*Pernick*
Crossed Roof Prism Interferometer—*Gould et al.*
Astronomical Refraction: Some History and Theories—*Mahan*
Durable Narrow Absorption Band Infrared Filters Utilizing Powdered Mineral Materials on Polyethylene Substrates—*Carlon*
Performance of the Beckman IR-7 Infrared Spectrophotometer—I. Frequency Reproducibility and Accuracy (630–4000 cm^{-1})—*Kreuger*
A Very High Temperature Infrared Cell for Pure Liquids or Solutions—*Fishman*
Control of a Ruling Engine by a Modulated Interferometer—*Babcock*
Thermal Radiation from a Hemispherical Source in Contact with an Infinite Plane—*Kester and Minardi*
Influence of Scattering on Fluorescence Spectra of Dilute Solutions Obtained with the Aminco-Bowman Spectrophotofluorometer—*Price et al.*
New Backscattering Computation and Tables for Dielectric and Metal Spheres—*Adler and Johnson*
Photoelectron Energy Distribution Measurements for 10 to 50 ev Photons with a Planar Analyzer and Electron Multiplier—*Heroux and Hinteregger*
Spectral Irradiance from Stars and Planets—*Ramsay*
An Ultraviolet-Sensitive Image Tube—*Skorinko, Doughty, and Feibelman*
Diffraction Anomalies in Grating Spectrophotometers—*Stewart and Gallaway*
Total Absorptance in the Infrared—*Burch and Williams*
Total Absorptance of CO, CH_4 in the Infrared—*Burch and Williams*
Total Absorptance of CO_2 in the Infrared—*Burch et al.*
A Microwave Powered Hydrogen Lamp for Vacuum Ultraviolet—*Warneck*
Emittance Measurements on Infrared Windows Exhibiting Wavelength Dependent Diffuse Transmittance—*Hatch*
Total Absorptance of Water Vapor in the Near Infrared—*Burch et al.*
Use of an Oxyacetylene Flame to Calibrate a Prism Spectrometer in the 10–30 micron region—*Dickey and Rogge*
Simulating the Solar Spectrum with a Filtered High-Pressure Xenon Lamp—*Boettner and Miedler*
Cloud Chamber for Optical Measurements of Aerosols—*Speyer*
Distortionless Interferometer Plate Mount—*Ramsey and Mugridge*
Nine-Channel Polychromator for Observation of Time-Dependent Spectral-Line Profiles—*Spillman et al.*
Fundamental Principles and Methods for the Calibration of Radiometers for Photometric Use—*Angstrom and Drummond*
Isocon Scan—A Low-Noise Wide-Dynamic-Range Camera-Tube Scanning Technique—*Cope and Borkan*
Polarization by Reflection and Some Optical Constants in the Extreme Ultraviolet—*Cole and Oppenheim*
Low Pressure Mercury Arc for Ultraviolet Calibration—*Childs*
Selected Ordinates for Solar Absorptivity Calculations—*Olson*
High-Precision Strain-Free Mounting of Large Lens Elements—*Deterding*
Design Theory for a Submersible Scattering Meter—*Tyler*
Total Absorptance by NO_2 Band in the Infrared—*Burch and Williams*

Thermal Imaging by Means of the Evaporograph

Gene W. McDaniel and David Z. Robinson

The development of a thermal imaging device which operates on the principle of differential evaporation (or condensation) of oil on a thin membrane is described. Section I,A summarizes the requirements of any thermal imaging method and develops the theory as applied to the particular case of the Evaporograph, emphasizing the consideration of scene temperatures near 20°C. It is shown that the greatest component of irradiance at the membrane is utilized in the evaporation of the oil layer. A presentation system which forms a visible image based on the phenomenon of light interference to detect differences in the thickness of the oil film is described. Theoretical calculations based on this system, assuming a reasonable minimum detectable thickness difference, indicate that a temperature difference of 1°C in the scene can be detected with an $f = 2$ optical system. Experimental results confirm this. The application of the Evaporograph to quantitative measurements is indicated. Section I,B describes experimental work on the three components of the Evaporograph, the infrared optical system, the transducer or cell, and the visual optical system. The two commercial models which have evolved from this work are described. These Evaporographs can detect a temperature difference of 1°C from a 20°C background and have a resolution of 10 lines per mm. Various applications are pictured and described.

I. Theory

A. Introduction

Thermal imaging is the process of producing a visible two-dimensional image of a scene by virtue of the differences in radiation reaching the aperture of the imaging device which apparently originate at various parts of the scene. This process depends upon the fundamental property that all bodies at temperatures above absolute zero emit thermal radiation in predictable amounts that depend upon the nature of the surface and its absolute temperature. The radiation actually reaching the imaging device is modified by other factors as will be shown.

Any thermal imaging process requires three elements:

1. An optical system which collects radiation reaching the aperture of the device and brings it to a focus to form an image of the scene.

2. A transducer which absorbs the radiation so focussed, thereby undergoing some change in its characteristics.

3. A presentation system which forms a visible image from the changes in the transducer characteristics and thus enables the eye to "see" the thermal image.

Both authors were with Baird-Atomic, Inc., Cambridge, Massachusetts; Dr. Robinson is now with the Office of the Special Assistant to the President for Science and Technology, Washington, D.C.

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There are many types of thermal image-forming systems which utilize various physical properties to convert the radiation image into a visual image. An excellent summary and analysis of various image-forming systems has been made by Weihe.[1] The device to be described utilizes a transducer based on the principle known as evaporography which can be classified as an "energy proportional transducer." This means that the response of an elemental area is proportional to the total energy that has been absorbed by that area since the beginning of the imaging process.

B. History

The principle of evaporography is one of the oldest methods of heat detection and is certainly the oldest type of thermal imaging device. Infrared radiation was first discovered by the famous English astronomer Sir W. Herschel in the sun's spectrum in the year 1800.[2] By placing a thermometer in various regions of the sun's spectrum he found that the maximum temperature was located beyond the red end of the visible spectrum. In 1840 his son, Sir J. F. W. Herschel, demonstrated the existence of absorption bands in the infrared region of the sun's spectrum.[3] Instead of a thermometer, Herschel placed a blackened piece of filter paper moistened with alcohol in the sun's spectrum. He noticed that in some places the paper became warm and the alcohol evaporated while in other areas (the absorption bands) no energy was received from the sun and the paper remained wet. This is the essential principle of evaporography.

This method of observation was forgotten for almost ninety years as people turned to bolometers and thermopiles for thermal detectors. Then, during the 1920's, Professor M. Czerny in Germany adopted this technique and developed most of the important features which are in use today.[4,5] For the filter paper Czerny substituted a thin membrane of lacquer; for an absorbing layer he used bismuth black evaporated on the membrane. In place of the alcohol he used a hydrocarbon oil. Finally, the entire system was enclosed in a housing from which the air was evacuated. Czerny used this transducer in conjunction with an infrared spectrometer to record infrared spectra.

C. Description of the Evaporograph

The Evaporograph[6] is, therefore, a thermal imaging device which converts an infrared image into a visible image by differential evaporation or condensation of oil on a thin membrane. The operation of the Evaporograph can best be understood by referring to the simplified diagram shown in Fig. 1.

In this thermal imaging process, the first element is a germanium lens which collects the infrared radiation and brings it to a focus to form an image.

The second element of this process is the transducer or detector which consists of a very thin nitrocellulose membrane placed at the image plane (see Fig. 2). This membrane is about 0.1 micron thick; so thin that white light reflected from the front and rear surfaces of the membrane presents the first-order yellow interference color. The front surface is coated with a thin layer of gold-black which will absorb radiation. The membrane is placed within an enclosure called a cell and the air is evacuated from both sides. The rear half of the cell is lined with blotter paper moistened with a few drops of oil. This half can be heated by an electric heater which slips over the outside surface of the cell.

The irradiance at the membrane due to flux focussed thereon by the germanium lens is absorbed by the gold black, producing a heating effect. Thus, under equilibrium conditions, minute temperature differences which form a thermal reproduction of the infrared image will be present over the surface of the membrane. Now if the cell is heated, the vapor pressure of the oil will increase until the dew point is reached, at which time the oil will begin to condense upon the surface of the membrane. The condensation rate at any point is dependent upon the temperature at that point. Therefore as time progresses, an oil film will be formed whose thickness varies from point to point to form a reproduction of the thermal pattern on the membrane. Thus, the differences in infrared radiation focussed on the membrane have been converted to differences in a physical quantity: the thickness of the oil film.

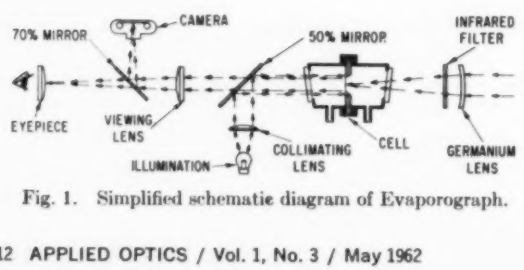

Fig. 1. Simplified schematic diagram of Evaporograph.

The third element of this process is termed the visual optical system. If the membrane is illuminated with white light the oil film pattern can be seen in different colors because of interference between reflections from the front surface of the oil film and the rear surface of the membrane. This is accomplished by a collimated beam of light from the illumination lamp reflected from the fifty percent mirror to the membrane. The useful light reflected from the membrane passes through the fifty percent mirror to the viewing lens which forms an image at the eyepiece. A seventy percent reflecting mirror placed in this beam directs light to a 35-mm camera. This allows the operator to observe and photograph the image simultaneously. Note that an infrared filter is required to prevent reflection of the illumination from the rear surface of the germanium lens back to the observer's eye.

D. Theory of the Evaporograph

1. *Introduction*

The general theory of thermal imaging has been covered by several authors[1,7,8] and will not be treated in detail here. However, the results will be summarized, and then the application to the evaporographic process will be developed.

In the analysis of thermal imaging of objects at temperatures below 100°C, the importance of considering all sources which contribute to the irradiation finally reaching the transducer must be stressed. For higher temperatures many of these sources are negligible and can be disregarded.

2. *Power Balance at Evaporograph Membrane*

For the purpose of this analysis a simplified model of the Evaporograph cell as shown in Fig. 2 will be used. Let the membrane divide the cell into two regions which are at temperatures T_1 and T_2 and assume black-body radiation within these volumes. An optical system at temperature T_1 and angular aperture 2α admits radiation from the scene to form an image on the membrane.

Consider a scene having a uniform background at a temperature T_B except for an area dA_T which is at a temperature T_T. Radiant flux from this scene passes through the intervening atmosphere at temperature T_1 to the entrance pupil of the optical system. Let the image on the membrane be da_T at a temperature T_T' with the surrounding area at temperature T_B' (see Fig. 3).

The energy incident upon the membrane can be separated into two portions:

1. That portion which originates outside of the imaging device and reaches the membrane via the optical system.

2. That part which comes from within the imaging device itself.

The first portion includes the desired energy from the area dA_T in the scene which is a function of the temperature T_T and the spectral emittance $\epsilon_T(\lambda)$ of the body which may be dependent upon the wavelength λ. However, as mentioned earlier, when this energy reaches the entrance pupil of the optical system it will have been modified by:

1a. Energy reflected from the area, dA_T, which is dependent upon the spectral reflectance, $\rho_T(\lambda)$.

1b. The spectral transmittance of the atmosphere $\tau_\lambda(\lambda)$.

1c. Energy emitted by the atmosphere at its temperature T_A, and spectral emittance, $\epsilon_A(\lambda)$.

The designer has no control over this radiant energy until it reaches the entrance pupil of the optical system. From this point the energy which finally reaches the membrane at da_T is further modified by:

1d. The spectral transmittance $\tau_0(\lambda)$ of the optical system.

1e. Energy emitted by the optical system due to its temperature T_1 and spectral emittance $\epsilon_0(\lambda)$.

The second part of the energy originates within the imaging device itself and, depending upon the imaging process used, some control over this portion can be exercised. Let the spectral absorptance and emittance of the two surfaces of the membrane be $\alpha_1(\lambda)$, $\epsilon_1(\lambda)$, $\alpha_2(\lambda)$, and $\epsilon_2(\lambda)$. It will be assumed that these quantities are not dependent upon the angle of incidence. In the special case of the Evaporograph, there is also a collimated beam of light from the visual optical system which is denoted by $H_\lambda(V)$. Summarizing, the energy reaching da_T from within the imaging device consists of:

2a. Black-body radiant energy from the front half of the enclosure at temperature T_1, excepting the solid angle subtended by the optical system.

2b. Black-body radiant energy from the rear half at temperature T_2.

2c. Radiant energy $H_\lambda(V)$ from the viewing system.

The energy content of the elemental area da_T can also vary by:

2d. Evaporation (or condensation) of oil (denoted by Q_4).

2e. Radiation from the front and rear surfaces (Q_5).

2f. Conduction along the surface of the element to the supporting member (Q_6).

2g. Convection losses to the air remaining within the cell (Q_7).

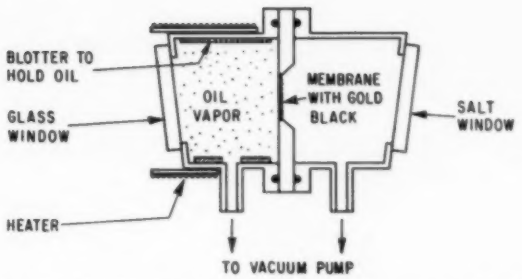

Fig. 2. Simplified schematic diagram of Evaporograph cell.

The sum of all of these energies must be zero. It must be remembered that the spectral radiant properties of these various elements are, in general, a function of the wavelength, so that integration over all wavelengths is required. Assuming that the irradiation on dA_T from its surroundings is black-body radiation at a temperature T_A and expressing the energies in terms of unit time, or power, one has:

$$E\,da_T\left\{\underbrace{\int_0^\infty \tau_A(\lambda)\tau_0(\lambda)\alpha_1(\lambda)[\epsilon_T(\lambda)W_\lambda(T_T)+\rho_T(\lambda)W_\lambda(T_A)]d\lambda}_{(1)}\right.$$
$$\left.+\underbrace{\int_0^\infty \tau_0(\lambda)\alpha_1(\lambda)\epsilon_A(\lambda)W_\lambda(T_A)d\lambda}_{(2)}+\underbrace{\frac{1}{\pi}\int_0^\infty \epsilon_0(\lambda)\alpha_1(\lambda)W_\lambda(T_1)d\lambda}_{(3)}\right\}$$
$$+\,da_T\underbrace{\left(1-\frac{E}{\pi}\right)\int_0^\infty \alpha_1(\lambda)W_\lambda(T_1)d\lambda}_{(4)}+da_T\underbrace{\int_0^\infty \alpha_2(\lambda)W_\lambda(T_2)d\lambda}_{(5)}$$
$$+\,da_T\underbrace{\int_0^\infty \alpha_2(\lambda)H_\lambda(V)d\lambda}_{(6)}+da_T\left[\underbrace{\int_0^\infty \epsilon_1(\lambda)W_\lambda(T_{T'})d\lambda}_{(7)}\right.$$
$$\left.+\int_0^\infty \epsilon_2(\lambda)W_\lambda(T_{T'})d\lambda\right]+q_4+q_6+q_7=0, \quad (1)$$

where $E=(1+4f^2)^{-1}$ and the small q's indicate power. The terms of this equation are as follows: (1) is the power per unit area emitted and reflected by the area dA_T in the scene; (2) represents the power radiated by the atmosphere between the scene and the viewing device; (3) is the power emitted by the optical system; (4) is the balance of the power received from the left due to the enclosure at temperature T_1; (5) is the power received from the right-hand hemisphere at temperature T_2; (6) is the power from the viewing light; (7) is the power radiated by the area of the membrane da_T. q_4 is the power absorbed by evaporation of oil from the membrane. q_6 represents the power loss by conduction along the film to the supporting surface. q_7 is the power loss by convection from the surface element da_T.

Actually we are interested in the power difference received at the membrane from the image of the area dA_T in the scene and an adjacent area dA_B at a background temperature T_B. An equation equivalent to (1) can be set up for this area dA_B and its image da_B. Note that terms (2), (3), (4), (5), and (6) will be identical for both cases. If we let $dA_T = dA_B$, which im-

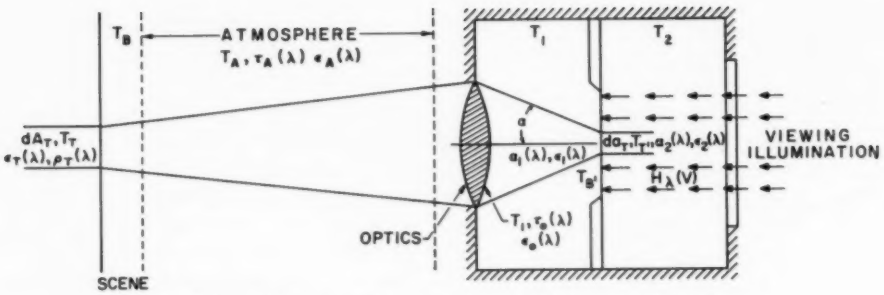

Fig. 3. Schematic diagram of power balance at Evaporograph membrane.

plies that $da_T = da_B$ and if the difference between T_T and T_B is sufficiently small that the spectral emittance of the surface and the spectral transmittances of the atmosphere and of the optics can be considered the same, then by subtraction one has:

$$E\int_0^\infty \tau_A(\lambda)\tau_0(\lambda)\alpha_1(\lambda)\ \epsilon_T(\lambda)\ [W_\lambda(T_T) - W_\lambda(T_B)]d\lambda = \int_0^\infty [\epsilon_1(\lambda) + \epsilon_2(\lambda)]\ [W_\lambda(T_{T'}) - W_\lambda(T_{B'})]d\lambda + \Delta q_4 + \Delta q_7. \quad (2)$$

This assumes that the power difference lost by conduction is negligible. Let us further assume that T_T does not differ appreciably from T_B; that is,

$$T_T = T_B + \Delta T \text{ where } \Delta T \ll T_B.$$

Also let us define mean values of the various transmittances, absorptances, and emittances according to the spectral distribution of the radiation concerned; viz.,

$$\tau_A = \frac{\int_0^\infty \tau_A(\lambda)W_\lambda(T_T)d\lambda}{\int_0^\infty W_\lambda(T_T)d\lambda}. \quad (3)$$

Then, substituting these values in Eq. (2), remembering that $\int_0^\infty W_\lambda(T_B)d\lambda = \sigma T_B{}^4$ where σ is the Stefan-Boltzmann constant, and neglecting terms of higher order, one obtains:

$$4\ E\tau_A\tau_0\alpha_1\epsilon_T\sigma T_B{}^3\ \Delta T = 4(\epsilon_1 + \epsilon_2)\sigma T_{B'}{}^3\ \Delta T' + \Delta q_4 + \Delta q_7$$

or, solving for $\Delta T'$,

$$\Delta T' = \frac{4E\tau_A\tau_0\alpha_1\epsilon_T\sigma T_B{}^3\Delta T - \Delta q_4 - \Delta q_7}{4\ (\epsilon_1 + \epsilon_2)\sigma T_{B'}{}^3}. \quad (4)$$

Equation (4) shows that $\Delta T'$ varies directly with the optical efficiency E, the transmittances of the atmosphere, τ_A, and of the optical system, τ_0, the emittance of the scene, ϵ_T, and the absorptance of the tranducer, α_1. It can also be increased by minimizing Δq_4 and Δq_7, and varies inversely with the transducer emittances, ϵ_1 and ϵ_2, and the transducer temperature, $T_{B'}$. If Δq_4 and Δq_7 are set equal to zero, one has the general equation for any thermal imaging device in which the losses due to sidewise conduction and convection are negligible.

Solving Eq. (4) for ΔT yields:

$$\Delta T = \frac{4(\epsilon_1 + \epsilon_2)\sigma T_{B'}{}^3\ \Delta T' + \Delta q_4 + \Delta q_7}{4E\ \tau_A\tau_0\alpha_1\epsilon_T\sigma T_B{}^3}. \quad (5)$$

Thus, if the convection loss, Δq_7, the power difference, Δq_4, required to evaporate a minimum perceptible thickness of oil, and the temperature rise, $\Delta T'$, are known, the minimum detectable temperature difference, ΔT, in the scene can be obtained.

3. *Theoretical Sensitivity*

Thus far the equations derived have considered the power distribution between the membrane and its environment under equilibrium conditions. As pointed out, the analysis is of a general nature and could be applied to any thermal imaging device with slight modifications. Consider now the specific case of the Evaporograph. This is an "Energy Proportional Transducer," which means that the response is proportional to the total energy that has been received since the imaging process was started. Suppose that an oil film is formed on the membrane and then the shutter is opened to admit radiation from the scene. What is the smallest radiation difference that can be detected in a reasonable time interval by the resulting change in oil film?

Of the total energy Q admitted by the optical system, only a portion is absorbed, the remainder being reflected or transmitted by the absorbing layer on the membrane. Harris[9] indicates that an "80% layer," i.e., one that absorbs 80% of the incident energy ($\alpha_1 = 0.8$) has the greatest efficiency.

This absorbed energy is dissipated as follows: (1) heating the absorbing layer (Q_1), (2) heating the membrane (Q_2), (3) heating the oil film (Q_3), (4) evaporating a portion of the oil film (Q_4), (5) reradiation losses (Q_5), (6) conduction losses (Q_6), and (7) convection losses (Q_7). These may be combined and expressed in terms of unit area as:

$$Q' = \int_0^\infty \alpha_1(\lambda) H_\lambda \Delta t d\lambda = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7,$$

where H_λ is the spectral irradiance falling on the absorbing layer and Δt is the time interval during which this irradiance has been present. It will be assumed that the conduction losses Q_6 are negligible.

Then under the proper conditions, the oil film on an elemental area, da_B, of the background will remain constant, while the oil film on the area da_T will evaporate to form a detectable thickness difference in a time interval Δt. To evaporate this oil thickness, the temperature of the area da_T must be raised an amount $\Delta T'$ above the temperature of the surrounding area. The energy required to produce and maintain this temperature increase is, for unit area:

$$Q' = (S_1\delta_1 d_1 + S_2\delta_2 d_2 + S_3\delta_3 d_3)\,\Delta T' + Q_4 + Q_5 + Q_7,$$

where

S_1 = specific heat of absorbing layer
S_2 = specific heat of membrane
S_3 = specific heat of oil
δ_1 = density of absorbing layer
δ_2 = density of membrane
δ_3 = density of oil
d_1 = thickness of absorbing layer
d_2 = thickness of membrane
d_3 = thickness of oil.

The difference in the reradiation losses, Q_5, between the areas da_T and da_B is

$$Q_5 = (\epsilon_1 + \epsilon_2)\sigma T_{T'}{}^4\,\Delta t - (\epsilon_1 + \epsilon_2)\sigma T_{B'}{}^4\,\Delta t,$$

where ϵ_1 and ϵ_2 are mean values as expressed by Eq. (3) and Δt is the time interval. In particular, if $T_{T'} = T_{B'} + \Delta T'$ and $\epsilon_1 = \epsilon_2 = 0.8$,

$$Q_5 = 1.6\sigma\,\Delta t\,[(T_{B'} \times \Delta T')^4 - T_{B'}{}^4] \approx 6.4\sigma T_{B'}{}^3\,\Delta T'\,\Delta t.$$

By substitution

$$Q' = (S_1\delta_1 d_1 + S_2\delta_2 d_2 + S_3\delta_3 d_3)\,\Delta T' + 6.4\sigma T_{B'}{}^3 \Delta T' \Delta t + Q_4 + Q_7. \quad (6)$$

The first bracket can be calculated as soon as the temperature rise $\Delta T'$ is known; also, the second term can be evaluated if $T_{B'}$ and $\Delta T'$ are known. Q_7 can be estimated if $\Delta T'$ and the partial pressure of the air are known. The term Q_4 which represents the energy required to evaporate the minimum detectable change in oil film thickness in a reasonable time remains. This term depends upon the physical constants of the oil and the thickness change required.

The value of Q_4 can be obtained as follows. First, from simple theory, the heat required is simply the mass evaporated per unit area multiplied by the latent heat of evaporation, or:

$$Q_4 = \Delta d\,\delta_3\,L, \quad (7)$$

where

Δd = the thickness change required
L = the heat of evaporation (cal/gm)

and the equation is written for unit area.

The temperature rise can be found as follows: Since the membrane is located in an evacuated chamber and is initially in equilibrium with the vapor pressure of the oil, the number of molecules striking a unit area per second, and hence the mass, can be calculated from kinetic theory. It is found to be[10,11]:

$$m(T_{B'}) = \theta\,(M/2\pi R T_{B'})^{1/2},$$

where

θ = vapor pressure
M = molecular weight
R = gas constant.

Since the film is in equilibrium with its vapor, this expression must also represent the amount of oil evaporating per square centimeter per second. Now, if the temperature of the material is raised by $\Delta T'$, there will be an excess amount of material leaving the surface, expressed by:

$$\Delta m = m(T_{B'} + \Delta T') - m(T_{B'}) = \left(\frac{M}{2\pi R}\right)^{1/2} \Delta T' \frac{\partial}{\partial T_{B'}} \frac{\theta}{\sqrt{T_{B'}}}.$$

Then,

$$Q_4 = \Delta m\,\Delta t\,L = L\,\Delta t\,\Delta T' \left(\frac{M}{2\pi R}\right)^{1/2} \frac{\partial}{\partial T_{B'}} \frac{\theta}{\sqrt{T_{B'}}}. \quad (8)$$

If θ is measured in millimeters of mercury, then (8) becomes:

$$Q_4 = 5.84 \times 10^{-2}\,\Delta t\,\Delta T' L \sqrt{M} \frac{\partial}{\partial T_{B'}} \frac{\theta}{\sqrt{T_{B'}}}. \quad (9)$$

Equation (9) is that derived by Czerny.[4]

This result can be carried further. The evaluation of $\partial/\partial T_{B'} = \theta/\sqrt{T_{B'}}$ can be accomplished by using the Clapeyron-Clausius[12] equation

$$\frac{\partial\theta}{\partial T_{B'}} = \frac{\theta L M}{R T_{B'}{}^2}, \quad (10)$$

where M is the molecular weight and L is the heat of evaporation per gram. Performing the indicated differentiation and substituting from (10) yields:

$$\frac{\partial}{\partial T_{B'}} \frac{\theta}{\sqrt{T_{B'}}} = \frac{\theta(2LM - RT_{B'})}{2RT_{B'}{}^{5/2}}. \quad (11)$$

Substituting this value in Eq. (9)

$$Q_4 = 2.92 \times 10^{-2} L\sqrt{M}\,\theta \Delta T' \Delta t (2LM - RT_{B'})/RT_{B'}{}^{5/2}. \quad (12)$$

By combining Eqs. (12) and (7) one obtains an expression for the increase in temperature $\Delta T'$ required to change the oil film thickness an amount Δd in a time interval Δt. This is found to be:

$$\Delta T' = \frac{R\Delta d\, \delta_2 T_{B'}^{5/2}}{2.92 \times 10^{-2}\, \Delta t \sqrt{M}\, \theta\, (2LM - RT_{B'})} \cdot \quad (13)$$

If the minimum perceptible thickness change Δd and the physical constants L and M of the oil used are known, then $\Delta T'$ can be computed and Eq. (6) evaluated to find the minimum detectable energy Q'.

In order to apply Eq. (13), it is necessary to know the vapor pressure of the oil at the operating temperature $T_{B'}$. It will be assumed that $T_{B'} \approx 300°K$. Since the data available do not extend to this temperature, it is necessary to extrapolate the data to this region.

It is possible to derive[12] from the Clapeyron-Clausius equation a formula relating the vapor pressure of a substance with its heat of vaporization and the temperature. This equation is of the form:

$$\ln \theta = C - \frac{a}{T}. \quad (14)$$

From this it is seen that a plot of $\ln \theta$ versus $1/T$ should be a straight line and the extrapolation can be easily accomplished.

The oils that were first used in the Evaporograph were the decanes. Table I lists the physical constants of these materials, together with the vapor pressure obtained by extrapolation.

Next, the amount of energy, Q_7, lost by convection to the air remaining in the cell can be estimated. Again from kinetic theory, the mass of air striking unit area per second is:

$$m_a = \theta_a (M_a/2\pi R T_{B'})^{1/2},$$

where

M_a = the average molecular weight of air

θ_a = the partial pressure of air in the cell.

Taking $M_a \approx 29$, $T_{B'} = 300°K$, and $\theta_a = 10\ \mu$, the result is

$$m_a = 1.8 \times 10^{-4}\ \text{gm cm}^{-2}\ \text{sec}^{-1}.$$

If these air molecules recoil at a temperature $T_{B'} + \Delta T'$, then in ten seconds the energy lost is

$$Q_7 = 2m_a \Delta T' \Delta t k_a,$$

where k_a is the specific heat of air which is 0.25 cal/gm. Substituting in the above expression gives

$$Q_7 = 9 \times 10^{-4} \Delta T'\ \text{cal cm}^{-2}. \quad (15)$$

It remains to decide on the minimum detectable thickness change under the most advantageous conditions. The membrane with its oil film is viewed by reflected light from an incandescent lamp which can be considered as a black-body source. Figure 4 shows the relation of the interference colors and the optical path differences when illuminated from such a source.

Although the details will not be given here, an analysis of the minimum perceptible color difference following the works of Kubota,[13] Brown,[14] and others has shown that the most sensitive regions are the first order gray and the first order purple. Their work shows an average value for the minimum detectable optical path difference to be 0.85 mμ. However, this cannot be achieved in practice due to inhomogeneities in the membrane and oil film pattern which obscure such subtle differences. A more realistic value taken from Fig. 4 would be 25 mμ.

It is now possible to compute the energy Q' required to maintain the temperature difference $\Delta T'$ for each oil. The results obtained are tabulated in Table II. These results are obtained from Eq. (6) with the following assumptions:

1. The membrane alone exhibits the first-order yellow interference color which means that the optical path difference between rays reflected from the front and rear surfaces is approximately 300 mμ. Assuming the index of refraction is approximately 1.5, the actual thickness is $d_2 = 100\ \text{m}\mu = 10^{-5}$ cm.
2. The optical thickness of the oil film is approximately 280 mμ. Since the index of refraction of all the oils is approximately 1.43, the actual thickness is $d_3 = 100\ \text{m}\mu = 10^{-5}$ cm.
3. Thermal mass of absorbing layer is 1.7×10^{-6} cal °C^{-1} cm^{-2}.
4. $T_{B'} = 300°K$.
5. Film thickness change $\Delta d = 25/2.86 = 8.7\ \text{m}\mu \approx 10^{-1}$ cm.
6. $\Delta t = 10$ sec, selected as a convenient time interval.

It is obvious from Table II that the greatest component of energy is Q_4, the energy required to evaporate the oil layer. The only other appreciable components are Q_5, the reradiation losses, and Q_7, the convection losses. Since this is true, Eq. (5) can now be used to determine ΔT, the minimum detectable temperature difference in the scene under these conditions.

Assume

$$\begin{aligned} \epsilon_T &= 1 \\ \alpha_1 &= \epsilon_1 = \epsilon_2 = 0.8 \\ E &= 0.059\ \text{(for an } f = 2 \text{ optical system)} \\ \tau_A \tau_0 &= 0.8. \end{aligned}$$

The salt window on the Evaporograph cell does not transmit beyond 19 μ. At temperatures near 300°K only 71% of the energy radiated is below this value. Therefore the denominator of Eq. (5) must be multiplied by 0.71 to correct for this effect. Taking values for hexadecane, which has proved to be one of the better oils, application of Eq. (5) results in

$$\Delta T = 1.8°C.$$

The best results obtained in the laboratory with an $f = 2.25$ optical system and approximately 20 sec viewing time showed a sensitivity of approximately 0.5°C.

Table I. Physical Constants of Substituted Decanes

Material	Molecular weight M	Density (gm/cc) δ_2	Specific heat (cal/gm) S_2	Vapor pressure (mm Hg at 300° K) θ	Index of refraction	Heat of vaporization (cal/gm) L
Dodecane	170.33	0.766	0.500	0.24	1.422	86.0
Tridecane	184.36	0.757	0.489	0.10	1.426	85.9
Tetradecane	198.38	0.765	0.497	0.04	1.429	85.7
Hexadecane	226.42	0.773	0.495	0.008	1.433	85.6
Octadecane	254.48	0.757	0.636	0.001	1.437	85.3

Table II. Energies Required for Minimum Detectable Thickness Difference

Material	$\Delta T'$(°C×10⁻⁴) Eq. (13)	Q_1 (cal cm⁻² ×10⁻⁶)	Q_2 (cal cm⁻² ×10⁻⁶)	Q_3 (cal cm⁻² ×10⁻⁶)	Q_4 (cal cm⁻² ×10⁻⁶)	Q_5 (cal cm⁻² ×10⁻⁶)	Q_7 (cal cm⁻² ×10⁻⁶)	Q' Eq. (6) (cal cm⁻² ×10⁻⁶)	Q' Eq. (6) (joules cm⁻² ×10⁻⁴)
Dodecane	0.90	0.00015	0.0007	0.0003	66	0.21	0.08	66	2.7
Tridecane	1.9	0.0003	0.0015	0.0007	65	0.44	0.17	66	2.7
Tetradecane	4.3	0.0007	0.0034	0.0016	65.5	1.0	0.39	67	2.8
Hexadecane	17.8	0.003	0.014	0.0068	66.2	4.2	1.6	72	3
Octadecane	117	0.02	0.094	0.056	64.6	27.5	10.6	103	4.3

4. *Figure of Merit*

The preceding analysis has shown that the largest term in Eq. (6) is Q_4, the energy required to evaporate the oil film. It is possible then to derive a figure of merit for the oil used.

The energy required to evaporate one centimeter of oil from a square centimeter of membrane surface is simply the heat of vaporization times the density of the oil. To obtain the energy required to evaporate an optical thickness of one centimeter, it is necessary to divide this value by the index of refraction. Thus,

$$\mathfrak{M} = \frac{L\delta_2}{n}, \tag{16}$$

where $\mathfrak{M}$ is the "figure of merit" and n is the index of refraction.

For the greatest sensitivity, this figure should be as small as possible. Selection of suitable oils can be guided by application of this figure of merit. Table III lists the figure for various materials. The exact choice of material will be influenced by other factors such as the effect of the oil on the membrane material, the ability to "wet" the membrane and form a continuous film, and the exact vapor pressure, which should be from 0.01 to 0.1 mm of mercury. Examination of Table III indicates that the tetramethyl siloxane polymers should result in better performance than the straight chain hydrocarbons. Those with suitable vapor pressures are the pentamer through octamer. An attempt was made to obtain these materials. Unfortunately, only crude fractions are available which are actually mixtures fractionated to give a certain viscosity. They are known as the Dow-Corning silicone 200 fluids. The viscosity of the pure materials ranged from 2.06 to 3.88 centistokes. Therefore, the mixture of 3 centistoke viscosity was obtained and has been used in later work. This material also has the advantage of a very low freezing point (−59°C) and therefore does not freeze on the membrane when operated in cold ambient conditions as do the hydrocarbons.

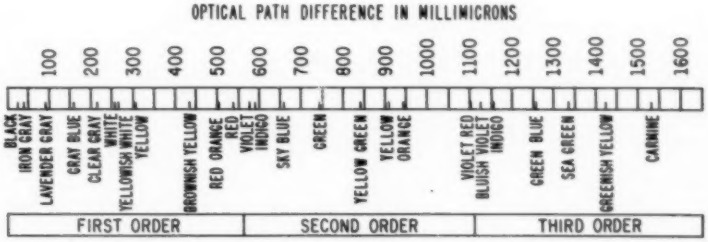

Fig. 4. Relation between optical path difference and interference colors.

Table III. Figure of Merit for Various Materials

Material	Figure of merit
Dodecane	45
Tridecane	44
Tetradecane	41
Hexadecane	43
Octadecane	43
d-Camphor	51.9
Tetramethyl siloxane polymers	
Trimer	27.7
Tetramer	23.6
Pentamer	20.2
Hexamer	17.9
Octamer	17.4

5. *Quantitative Measurements*

Equation (13) implies that, within limits, the thickness change in the oil layer is proportional to the temperature rise of a unit area of the membrane, or

$$\Delta d \propto \Delta T'.$$

For given operating conditions $\Delta T'$ can be related to the corresponding change in scene temperature ΔT. Thus, it is possible to make quantitative measurements of scene temperatures. However, such measurements are difficult because there is no simple direct method of determining Δd. Also, in practice this problem is complicated by variations in the membrane from point to point. Of the various methods tested, the most accurate results have been obtained with the photographic method which will be briefly described.

As in the foregoing analysis it is assumed that the major portion of the energy entering or leaving a unit area on the membrane is utilized to evaporate or condense the oil film. Thus, one can write:

$$\Delta X_n = A_n \Delta t, \tag{17}$$

where

ΔX_n = change in oil film thickness at point n
Δt = time required to produce this change
A_n = a constant for any particular point.

This linear relation of film thickness with time has been verified experimentally by using monochromatic illumination and determining the film thickness by standard interferometric methods.

The system parameters can be eliminated by use of a reference source in the field of view whose emissivity is known, or is the same as that of the surface whose temperature is to be determined.

The constant A_n can be expressed in terms of the radiant emittance of the scene and system parameters. For the point at which the reference source is imaged, one can write:

$$X_0 - X_R = KW_R \Delta t, \tag{18}$$

where

X_0 = the film thickness at time $t = 0$
X_R = the film thickness after time Δt
W_R = the radiant emittance of the reference source
K = a constant, positive for evaporation; negative for condensation.

Now, if the instrument shutter is closed, the membrane will receive radiation equivalent to the ambient temperature of the cell, and a second equation can be written:

$$X_0 - X_{CR} = KW_{CR} \Delta t, \tag{19}$$

where X_{CR} is the film thickness at the reference image point after time Δt and W_{CR} is the equivalent radiant emittance corresponding to ambient temperature T_C. Subtracting (19) from (18) and rearranging, one obtains

$$(W_R - W_{CR})\Delta t = K'(X_{CR} - X_R). \tag{20}$$

Similarly, for the image point of the desired object in the scene

$$(W_T - W_{CT})\Delta t = k'(X_{CT} - X_T). \tag{21}$$

If the film thicknesses can be determined, then all the values of (20) are known except K′. Substituting this value in (21) allows the computation of W_T from which the temperature can be determined.

It is known that if monochromatic illumination is employed, the intensity of the reflected light will go through maxima and minima as the film thickness varies. If this reflected light is photographed on black and white film, the resulting optical density on the image will also vary from a maximum to a minimum. However, it has also been found that if white illumination is used and the images are photographed in color, similar changes in "density" readings of the processed film can be obtained if a color-sensitive densitometer is used. Figure 5 shows the variation in density units as the oil film condenses. Note that there are two linear regions on the density versus condensation time (film thickness) curve. In these regions, the film thickness can be expressed by:

$$X = K_1 D + K_2,$$

where D = density. Then Eqs. (20) and (21) can be rewritten as:

$$(W_R - W_{CR})\Delta t = K_1(D_{CR} - D_R) \tag{22}$$

and

$$(W_T - W_{CT})\Delta t = K_1(D_{CT} - D_T). \tag{23}$$

Therefore, if photographs are chosen in which the densities of all of the desired image points are within one or the other of these linear regions, then Eqs. (22) and (23) can be applied directly to determine W_T and from this the temperature can be computed.* *see p. 319*

(* If the densities do not lie in these linear regions, extrapolation can be employed. Also, in practice, the membrane thickness is never uniform over the entire surface. Hence a correction must be made for this condition. Methods for this have been developed, but will not be described here.)

II. Experiments and Applications

A. Experimental Work

1. Introduction

Much experimental work has been done on the various components of the Evaporograph guided by the theory which has been developed and set forth in Eqs. (6) and (13). This work can be divided into three portions, each of which pertains to one component of the thermal imaging process, i.e., (1) the infrared optical system, (2) the transducer or Evaporograph cell, and (3) the presentation system.

2. Infrared Optical System

As shown in Eq. (4) the temperature difference developed at the membrane is directly proportional to the efficiency of the optical system. Reflecting optical systems of the Newtonian and a modified Cassegranian type have been used. These systems have the advantage of freedom from chromatic aberration. However, because of mechanical limitations, they are necessarily of long focal length, greater than twenty centimeters. This restricts the field of view and results in a telescopic-type optical system.

Refracting optical systems using a germanium lens have also been used. Such a system can be made of relatively short focal length with the resulting wide field of view. They have the disadvantages of restricting the imaging device to wavelengths within the transmission band of the lens material, and also introduce chromatic aberration. In addition, an infrared filter must be placed in back of the lens to prevent reflection of the illumination from the visual optical system by the mirrorlike surface of the lens.

Each of these optical systems performed as expected.

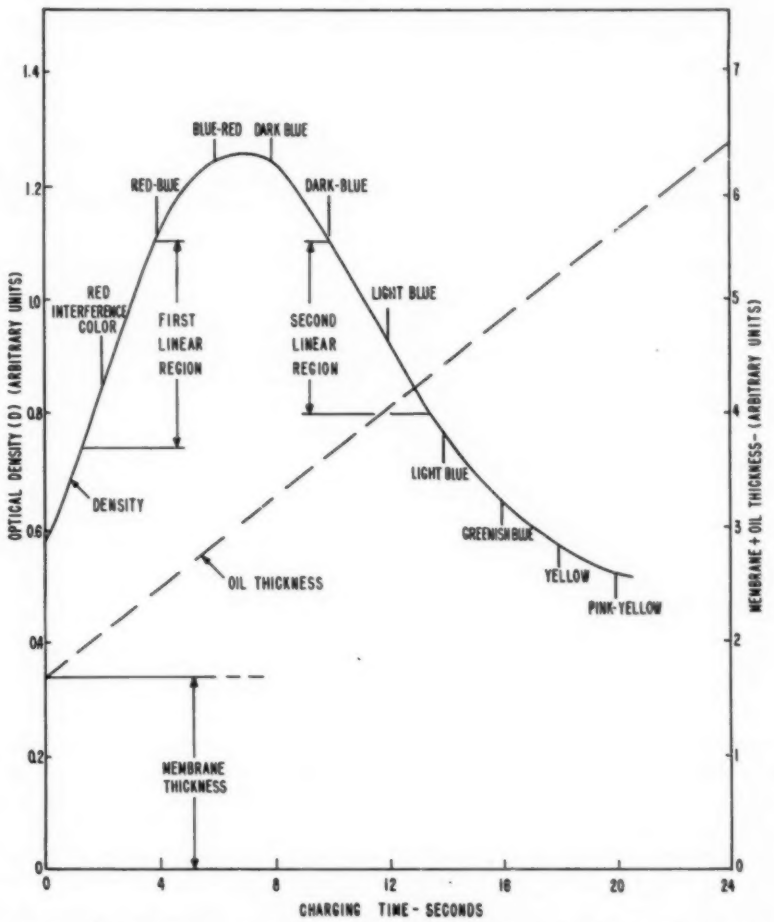

Fig 5. Oil film thickness and photographic density as a function of condensation time. (White light and color film.)

The use of any one of them will be dictated by the needs of a particular application.

3. *Transducer or Evaporograph Cell*

The Evaporograph cell depends upon three components: (a) the supporting layer or membrane, (b) the absorbing layer, and (c) the active material.

The supporting membrane must be a very thin uniform sheet of material with considerable strength and free from pin holes. The sheet should be approximately 0.1 μ thick. Various materials have been used for these films. The ones found most useful are listed below:

1. Amylacetate.
2. Polyvinal formal in dioxane or ethylene dichloride.
3. Polystyrene or benzene solution of Resogloz.
4. Nitrocellulose in acetone.

The films are usually formed by flotation on water, as described by Czerny,[15] Harris,[16] and others. The nitrocellulose membranes have proved to be most satisfactory and are in general use.

Experiments have also been made with aluminum oxide membranes, following the methods described by Hass[17] and Strohmaier.[18] These membranes have the advantage of very uniform thickness which is easily controllable. They have the disadvantages of reproducing the surface finish of the aluminum film which must, therefore, be of optical quality, and are somewhat more brittle than the nitrocellulose membranes. In addition, it was found to be very difficult to deposit the active material on the surface of the aluminum oxide in a uniform continuous film.

4. *The Absorbing Layer*

The absorbing layer must have a high absorptivity over the infrared region to be utilized. It should have a low heat capacity and must transmit the heat distribution from its receiving surface to the supporting layer with as little loss of definition as possible.

Gold black. In most of our work gold black has been used as the absorbing layer, formed by the method described by Harris.[9] The gold is evaporated from a tungsten filament in an atmosphere of hydrogen at a pressure of five to ten millimeters of mercury. The deposit has a very uniform absorptivity in the region from one to fifteen microns and has low thermal mass.

Metallic layers. As shown by Hadley,[19] if a metallic layer is evaporated on the membrane such that the resistance per square is 189 ohms, it will absorb 50% of the incident radiation, reflect and transmit 25%. This method is not adaptable to the Evaporograph as presently used because of the high reflection from the metalized front surface of the membrane which makes it impossible to obtain the interference colors which are the basis for the detection of the thickness of the active material.

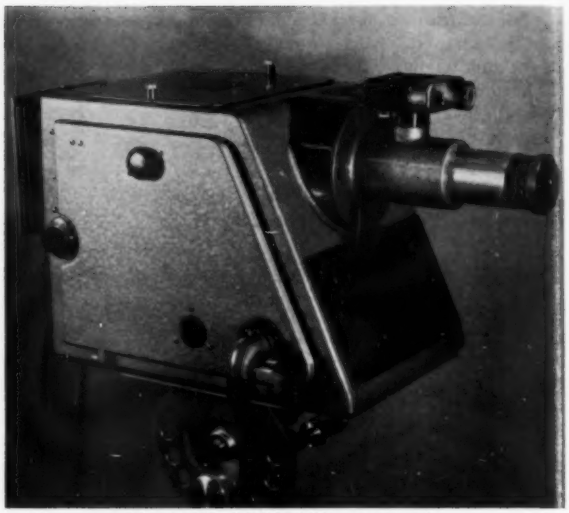

Fig. 6 Model KR 1 Evaporograph.

Other materials. Other investigators have used various materials such as lamp black, bismuth black, and metallic black of zinc.

5. *The Active Material*

The active material must condense or evaporate from the surface in such a manner that the temperature differences in the thermal image can be detected. The ideal material should have the following characteristics:

1. It should form a uniform layer on the membrane with no droplets; i.e., it should wet the membrane.
2. It should not attack the membrane or the apparatus.
3. It should not be a mixture of substances having widely different vapor pressures. Its physical characteristics should be such as to maximize the "figure of merit" derived in Eq. (16).

Two solid materials—camphor and naphthalene—have been used successfully by Czerny. The best results have been obtained with the paraffin oils, in particular with hexadecane and with the siloxane polymers. The best over-all operation has been obtained with the siloxane polymers which are available as the Dow-Corning silicone 200 fluids.

6. *Presentation System*

The presentation, or visual optical system of the Evaporograph, makes use of the phenomenon of light interference. Tests have been made with both monochromatic and white sources of illumination. There is little or no difference in sensitivity between the two types of sources. When a white source of illumination is used there is a definite relation between the oil film thickness and the interference color seen, as indicated in Fig. 5. Thus, there is no ambiguity as to which points of the image are warm and which are cold.

As indicated in Eq. (13), the sensitivity is directly proportional to the minimum thickness difference, Δd, of the active material that can be detected. Thus, any method of presentation which could operate with a smaller thickness difference would result in a corresponding increase in sensitivity. One type of viewing system which immediately comes to mind is phase contrast. However, this method cannot be directly applied because the reflection from the rear surface of the membrane interferes with the desired reflection from the front surface. In addition, the membrane must be extremely flat and the entire alignment of the optical system is critical.

B. Production Evaporograph

1. Introduction

The experimental work described has resulted in the development of two models of the Evaporograph.[20] The model JZ-1 Evaporograph employs a Newtonian telescope for the infrared optical system with an f = 2.25 aperture and a 20 cm focal length. The angular field of view is 5°.

The model KR-1 Evaporograph uses a germanium lens optical system with aperture f = 1.6 and a 7.5 cm focal length. The field of view is approximately 14°. This model is pictured in Fig. 6. The instrument can be focused down to object distances of 15 cm, resulting in a one to one image size, and features a coupled range-finder type focusing aid.

Both models have sensitivities of at least 1°C in the scene above a background temperature of 20°C and with surfaces of high emittance. With a standard parallel-bar type resolution chart having a background temperature of 20°C and a "line" temperature of 30°C, the maximum resolution is ten lines per millimeter on the membrane.

2. Model KR-1 Evaporograph

Figure 7 is a schematic diagram of the optical system of the model KR-1 Evaporograph. The infrared optical system consists of an f = 1.6 germanium lens with a 7.5 cm focal length. This is equipped with an iris diaphragm and shutter, and an infrared filter to prevent unwanted reflection of the viewing illumination from the rear surface of the lens. The Evaporograph cell is located at the focal plane of the lens. The cell and germanium lens assembly are mechanically coupled to a ground glass screen and a glass lens which has the same focal length as the germanium lens. To focus the instrument, the entire assembly can be moved to one side, so that the ground glass and lens will be on the optical center line. The field of view and focus can now be visually adjusted. When the cell is returned to the operating position, the same field of view will be in focus on the membrane.

There is an incandescent lamp bulb labeled "operational clear light" which is positioned between the Evaporograph cell and the germanium lens. This lamp serves three functions:

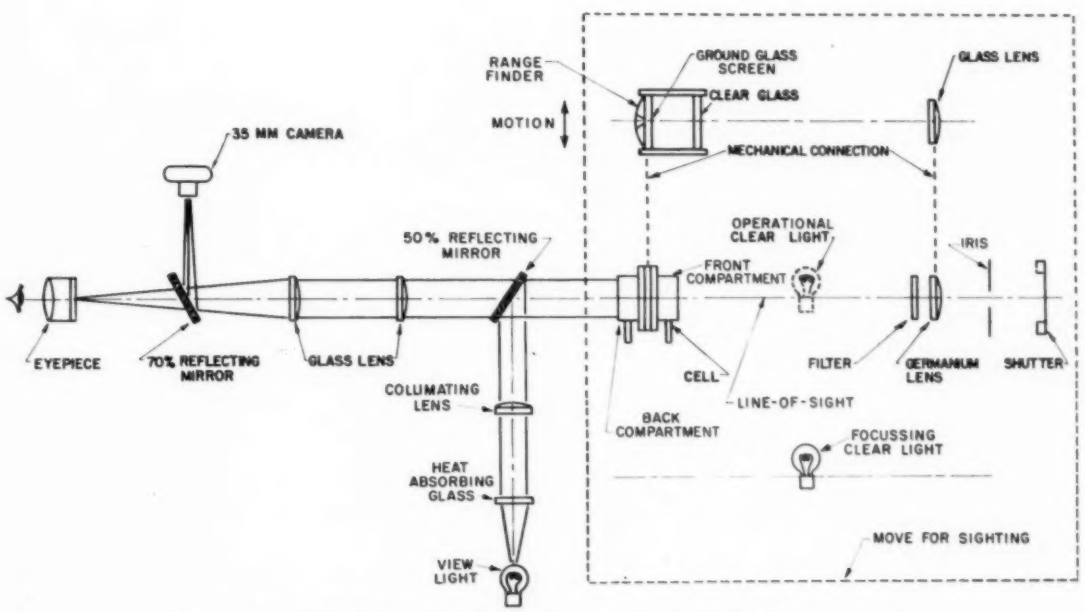

Fig. 7. Schematic diagram of the optical system of the model KR-1 Evaporograph

1. During stand-by conditions, it floods the membrane with radiant energy, thereby warming it so that no oil will condense.

2. It also warms the front compartment of the cell, preventing any oil condensation within.

3. During operation, after the oil film has increased beyond the usable range of thickness, a few seconds' exposure to the clear light will warm the membrane and evaporate the oil so that a new imaging cycle can begin. For this purpose, the clear light is mounted on a swivel which enables the operator to swing it in and out of the optical path as desired.

The visual optical system consists of an automotive-type lamp placed at the focus of the collimating lens. Parallel light from this lens is reflected from the 50% mirror to the membrane in the cell. The reflection from the membrane then passes through the 50% mirror to a pair of lenses which form an image of the membrane at the eyepiece and at the film plane of the camera.

3. *Operation*

The construction of the Evaporograph cell as shown in Fig. 2 is quite different from that of Czerny. In Czerny's model, the oil is contained in a small reservoir in which an electric heater is immersed. The reservoir can be rotated into position in front of the membrane. When desired, the reservoir is positioned and the heater is turned on. Oil then evaporates from the heater and deposits on the membrane in much the same manner as an aluminum coating is applied to a mirror. When the desired film thickness is attained as indicated by the interference colors, the heater is turned off and the reservoir swung away from the membrane. The thermal image can now be seen as the oil layer evaporates from the membrane.

In the cell construction used here, the oil is contained within an absorbent layer on the inner periphery of the cell wall. The entire wall is warmed by the heater which slips over the outside. This heats the oil, raising the vapor pressure to the point where oil will begin to condense upon the surface of the membrane. Two methods of operation are now possible:

1. The scene can be focused on the membrane. Then, as soon as the clear light is removed from the front of the cell, condensation of oil on the membrane will begin. The rate of condensation at any point will depend upon the irradiance at that point, so that an oil film will build up having thickness variations which reproduce the thermal image on the membrane. This method of operation should appropriately be termed the Condensograph method, since the image is formed as the oil is condensing upon the membrane.

2. Conversely, if there is sufficient irradiance at the membrane, the shutter can be closed and the clear light removed, allowing an oil film to form on the membrane. When it has reached the desired thickness, the shutter is opened and the thermal image will now cause the film to evaporate at a rate depending upon the local irradiance. Thus, the image will become visible. This is the true Evaporograph method of operation.

Both methods can be used with this cell design and each has its own advantages. In general, for scene temperatures below 50°C, the Condensograph method is preferred, while for higher temperatures, the Evaporograph method must be used.

4. *Applications*

The Evaporograph has proved to have many applications, only a few of which can be illustrated here. There has been great interest by the medical profession[21] in the use of thermal imaging for diagnostic purposes. The possibilities are indicated in Fig. 8, which shows a girl holding a cold glass of water. The detail apparent in the skin, clothing, hair and glasses demonstrate the results that can be obtained. Figure 9 is the image of a seated man afflicted with phlebitus of the left leg. The temperature difference between the two legs is obvious.

Figure 10 shows the image of Boston Harbor as seen from downtown Boston at night. The large smoke stack in the foreground is unmistakable, as well as two smaller stacks to the right. Careful examination shows that Logan Airport can be seen against Boston Harbor in the background. This is located at a distance of approximately eight miles.

Figure 11 depicts an unusual application in which a filament of Fiberglas is examined as it is being drawn from a platinum nozzle. The dark streak extending out of the picture is the filament of glass emerging from the cone-shaped molten glass visible as it issues from the nozzle. The light irregular band above the cone is a deposit of glass which has congealed on the outside surface of the nozzle. The nozzle itself appears cool because of the low emissivity of the platinum. By means of the techniques already described it was possible to measure the temperature gradient along the Fiberglas filament and cone.

Other applications include the following:

1. Nondestructive testing of bonds and other joints.

2. Thermal studies of process equipment, such as heat exchangers.

3. Wind tunnel temperature observation.

4. Observation of electronic assemblies to locate hot spots.

5. Observation of in-service blast furnaces to locate dangerously thin areas in the furnace lining or the formation of scabs within.

6. Observation of high power switch gear and power distribution systems to locate faulty joints or contacts before actual burnout occurs.

Fig. 8. Evaporograph image of a girl holding a glass of cold water.

Fig. 9. Evaporograph image of a seated man afflicted with phlebitus of the left leg.

Fig. 10. Evaporograph image of Boston Harbor at night.

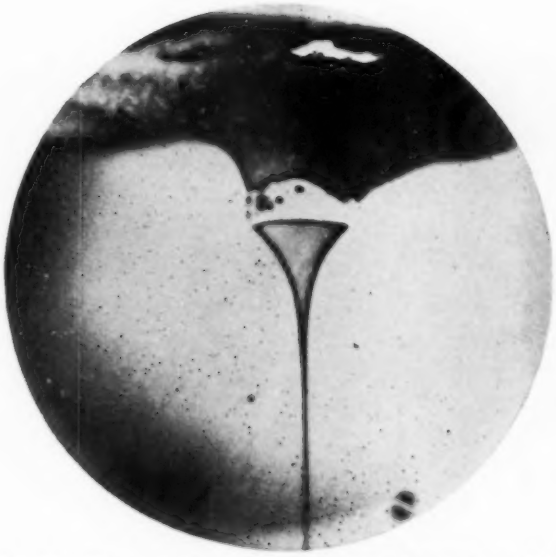

Fig. 11. Evaporograph image of a filament of Fiberglas as it is being drawn.

7. Inspection of infrared optical materials and systems.

Conclusions

The Evaporographic method of thermal imaging is an outstanding example of the application of simple principles to obtain a useful device. Its very simplicity allows the construction of a small, light-weight device capable of operating under extreme environmental conditions. The ideal design of the Evaporograph awaits the development of more permanent membranes and of a sealed-off cell that would require no vacuum pump. A different presentation system that could operate with smaller differences in oil thickness would result in a corresponding direct increase in sensitivity. The sensitivity at present is several orders of magnitude away from the ultimate limit imposed by the statistical nature of the evaporation (or condensation) process.

Many persons have contributed to the development of the Evaporograph as described herein. In particular, the authors wish to recognize the work of A. P. DiMattia who has assisted in all phases of the development, of Mrs. J. Gillingham for many hours spent in testing and evaluating oils, blacks, and membranes, and of Mrs. W. Hampton who has mastered the art of membrane making.

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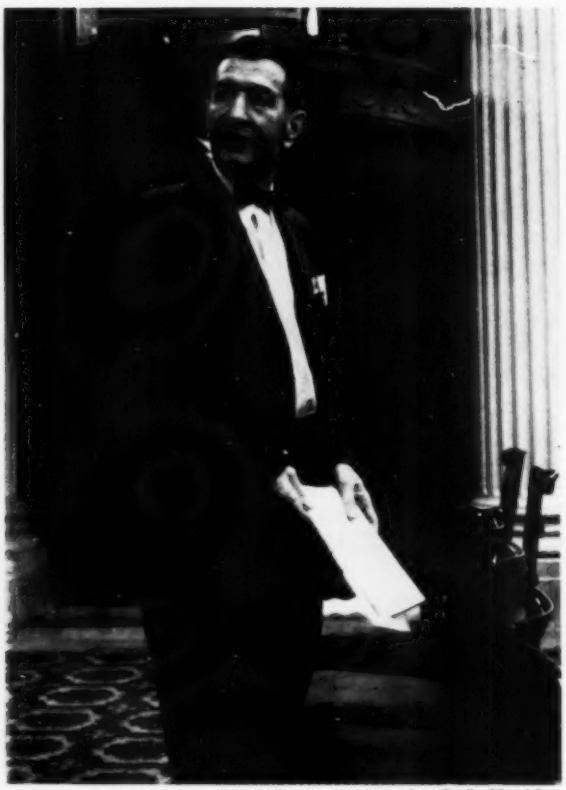

photo D. L. MacAdam

The new Treasurer of the Optical Society of America Archie I. Mahan and author of a paper on refraction in the July issue.

Participating in the July 1961 ICO London sessions are G. Novarski *Paris,* A. N. Other, D. Marquis *Cape Canaveral,* Stanley S. Ballard *Fla.,* P. Fleury *Paris,* and W. Wolfe *IRIA.*

J. Dyson *London,* R. E. Hopkins *Rochester,* and two other participants in the July 1961 London ICO Meeting.

A Calorimeter for Energy Measurements of Optical Masers

Tingye Li and S. D. Sims

A calorimeter for measuring the output energy of optical masers has been made. It consists essentially of several thermistor beads connected in a bridge circuit and placed in intimate contact with a carbon cone into which the maser beam is directed. The instrument is wide band and easily calibrated. A description of the calorimeter and some results of energy measurements of a ruby optical maser are presented in this paper.

Introduction

The output energy of a pulsed ruby optical maser has been measured recently by Maiman *et al.*[1] and by Collins and Nelson.[2] Their measurements have involved the use of calibrated phototubes whose output is proportional to the incident power. The total energy incident upon the phototube was obtained by a time integration of its output.

We have constructed a calorimeter which is capable of measuring energy directly over a very wide band of wavelengths. It is simple, stable, and easily calibrated. We have used it to measure the output energy of a ruby optical maser as a function of the input energy to the flash lamp and of the transmission of the output mirror on the ruby rod. A description of the calorimeter and some results of the measurements are presented in this paper.

The Calorimeter

Principle of Operation

The present instrument was inspired by a calorimeter constructed for power measurements at millimeter wavelengths.[3] The principle of operation involves essentially the efficient conversion of optical energy into heat which in turn produces a measurable temperature rise of the transducer. This is achieved by directing the collimated maser output beam into the open end of a carbon cone which serves as the transducer. The temperature rise of the cone is measured by thermistor beads in intimate contact with the cone and connected in a bridge circuit. The output of the bridge is fed to a dc amplifier driving a recorder (see Fig. 1).

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Received 13 December 1961.

In order to minimize drift due to ambient temperature variations, two identical cones with matching thermistors are connected to form a conjugate branch pair in the bridge circuit. Thus, ambient temperature variations produce equal changes in both cones and the net effect is canceled out in the output circuit of the bridge.

For calibration, a condenser containing a known amount of electrical energy is discharged through the active cone by means of a pair of contact rings. Once the resistances of the cone and of the discharge circuit are determined, the amount of energy dissipated in the cone can be calculated, and hence the maximum deflection on the recorder is easily calibrated in terms of energy.

The instrument can also be used to make power measurements of c.w. optical masers by directing the maser beam into one of the cones while sending a known amount of current through the other cone to balance the bridge. In this case it is important to have the cones and the thermistors as similar as possible. However, errors arising from possible differences can be greatly reduced by making a second measurement interchanging the role played by each cone.

Physical Description

A sketch of the carbon cone is shown in Fig. 2. The opening at the base of the cone has a diameter of 1 cm. The mass of the cone, and hence its over-all size, is dictated by sensitivity requirements. The cones in the present instrument weigh $^1/_3$ gm each. Three thermistor beads are embedded in a slot on the outer surface of the cone and are held in place by glyptol. The thermistors are Western Electric Type 23A and are connected in series. The contact rings for calibration are formed by 125-μ platinum wires lying in V-grooves and bonded to the cone with silver paste to insure good electrical contact. The positions of the

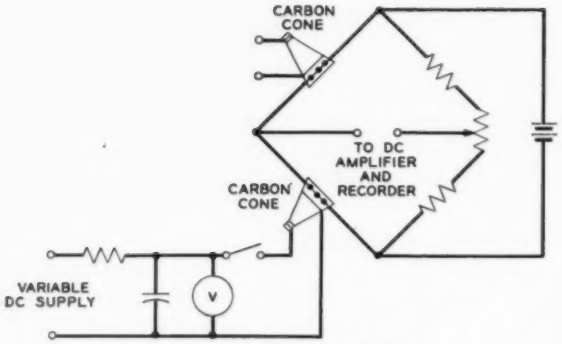

Fig. 1. Schematic of the calorimeter.

contact rings are chosen to give the same heat distribution for the maser pulse and the calibration pulse so that the response curves are similar. A 25-μ mica window glued to the open end of the cone prevents heat loss due to convection. The cone is supported by a polyfoam block inside a metal case containing a hole for the maser beam to enter. Two identical units with matching thermistors are made and are connected in conjugate branches of the bridge circuit. Either unit can be used as the active transducer. All elements of the bridge circuit, including both transducer units, resistors, and potentiometers, are mounted in a box which reduces further the effects of convection. The box is provided with a quartz window for the maser beam to enter.

Calibration and Sensitivity

In order to determine the amount of energy dissipated in the cone during calibration, the resistance of the cone and the residual resistance in the discharge circuit must be known. The resistance of the cone is small—about $^1/_{10}$ ohm—varying slightly from cone to cone. The residual resistance in the discharge circuit used for calibration is determined by noting the time constant in the discharge decay curve as observed on a cathode-ray oscilloscope. In our setup, with a heavy-duty discharge switch and 50 mylar condensers (4-μf each) connected in parallel, the residual resistance is about the same as the resistances of the cones.

A recording of the response of the calorimeter to a calibration pulse is shown in Fig. 3(a). The rise time of the curve is governed principally by the time required for the heat to redistribute itself in the cone and to travel to the thermistors. The decay time is very much longer and is determined by the rate at which the cone loses heat to its surroundings. Figure 3(b) shows the response of the calorimeter to a maser pulse. The rise time in this case is somewhat shorter and therefore a slight correction must be made in reading the response curves. This can be done either by extending the response curve of the calibration pulse near its maximum by a small amount to match the shape of the response curve of the maser pulse and taking the extended maximum as a measure of energy, or by reading the response curves at a later instant where the initial discrepancy between the two curves has disappeared.

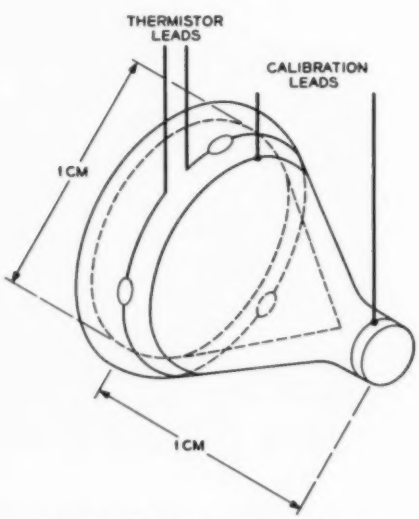

Fig. 2. The carbon-cone transducer.

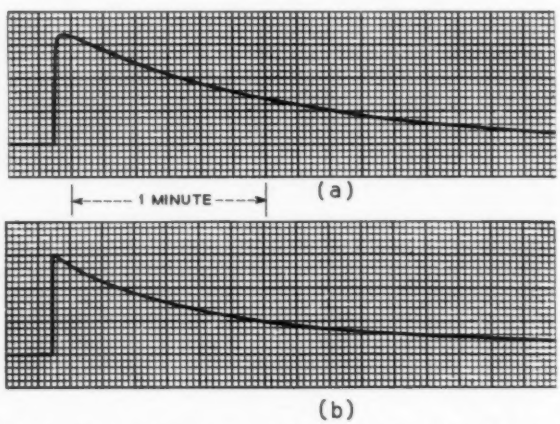

Fig. 3. (a) Response curve of the calorimeter to a calibration pulse; (b) response curve of the calorimeter to a maser pulse.

The calibration curve for the entire system is given in Fig. 4 on log–log paper. The abscissa is the extended maximum of the response curve of the system to a calibration pulse as recorded on a Sanborn recorder, and the ordinate is the energy dissipated in the cone. All data points fall on a straight line having a slope very close to 45 deg. This means that the response of the system to input energy is almost linear. The slight nonlinearity is presumably due to the nonlinear behavior of the thermistors.

The sensitivity of the calorimeter is 50 mv per joule at the output of the bridge circuit. It can be increased

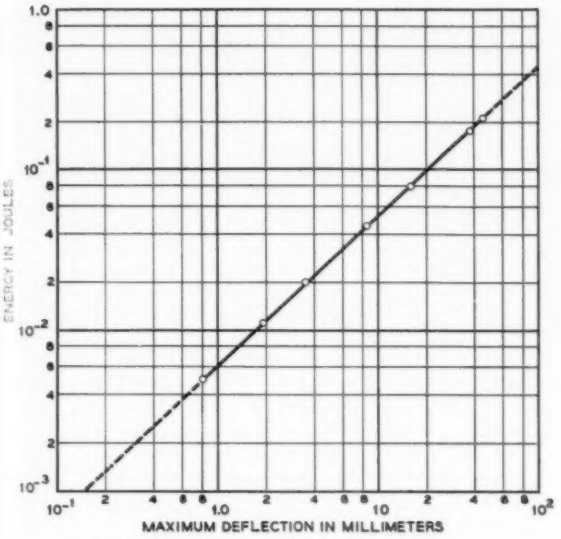

Fig. 4. Calibration curve for the calorimeter.

by either decreasing the mass of the cone, increasing the number of thermistors, or increasing the supply voltage to the bridge. Since the system is extremely stable, the sensitivity can be increased further by the use of higher gain amplifiers.

The accuracy of the instrument depends not only on the accuracy with which the various parameters (e.g., the resistance of the cone, the residual resistance in the discharge circuit, the capacitance of the discharge condenser, etc.) are known, but also on the ability to match the shapes of the response curves of the maser pulse and of the calibration pulse. The response curve due to the calibration pulse would depend on the position of the contact rings on the cone while that due to the maser pulse would depend on the alignment of the maser beam. We believe the over-all error involved in our measurements to be about 10%.

The quartz window on the box and the mica window on the cone have a combined transmission of 83% at 6950 Å. This must be taken into account when using the calorimeter for energy measurements of the maser.

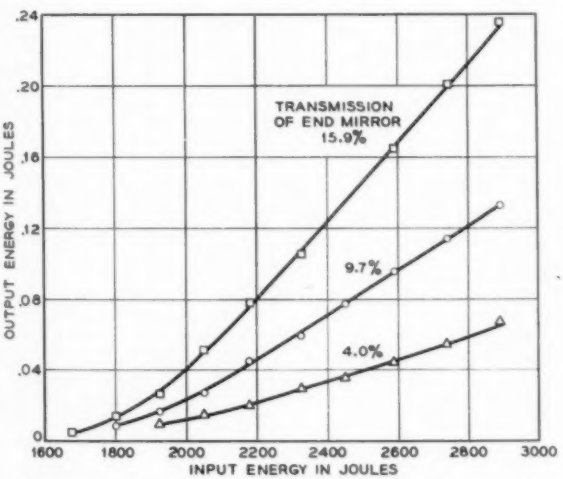

Fig. 5. Curves of the output energy of the pulsed ruby optical maser versus input energy to the flash tube. The three curves are for the same ruby rod but with the output end mirror silvered for three different values of transmission.

Measurements and Results

Energy measurements, using the calorimeter, were made on a pulsed ruby optical maser employing an FT-524 xenon flash tube as the pump source. The flash tube sits in a magnesium-oxide cylindrical reflector and is energized from a power supply containing a 400 μf bank of condensers. The ruby rod has a diameter of 0.6 cm and a length of 5 cm. The chromium concentration in the ruby is 0.05% and the optic axis is parallel to the axis of the rod. The temperature of the ruby was monitored by means of a thermocouple to insure that each measurement was made at the constant temperature of 25°C.

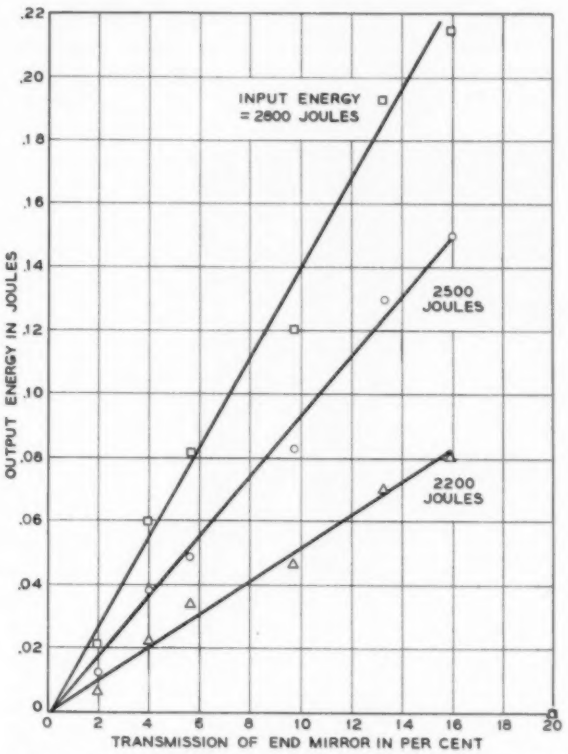

Fig. 6. Curves of the output energy of the pulsed ruby optical maser versus transmission of the output end mirror for three different constant values of input energy.

A typical set of data taken of the output energy of the maser as a function of the input energy to the flash tube is shown in Fig. 5. Each curve was taken with the output end mirror of the ruby resilvered for a

different value of transmission, the other end being fully opaque. Measurements were also made of the output energy of the flash tube in the green and violet absorption bands of the ruby as a function of the input energy, and a linear relationship was found to exist in the range of interest (1500 to 3000 joules input). Therefore, the abscissa in Fig. 5 can be taken as proportional to the pumping level of the maser.

Figure 6 shows a set of curves giving the output energy versus transmission of the output end mirror for various input energies. At 20% transmission no maser action was observed up to 3500 joules of input energy. While no mirrors between 15% and 20% transmission were tested, we presume that these curves would exhibit maxima in this range. Therefore, the optimum value of transmission for this particular ruby at 25°C is somewhere in the neighborhood of 18%. This optimum value should vary with temperature and with different rubies.

We wish to thank A. G. Fox and W. M. Sharpless for stimulating discussions and F. A. Braun and J. H. Hammond for assistance in the construction of the calorimeter.

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H. Hönl and K. Westpfahl *Freiburg,* two of the authors of an article on diffraction in the *Handbuch der Physik.*
photo F. S. Harris

ICO 1961 Paris Meeting participants during the Saint Gobain trip include H. H. Hopkins *Imperial College,* K. M. Greenland *British Scientific Instrument Makers Research Association,* A. Marèchal *Institut d'Optique,* P. Fleury *Institut d'Optique,* V. Garino-Canina *Cie. de Saint-Gobain,* P. R. Wakeling *O.S.A.,* C. G. Wynne *Imperial College,* and H. Lowen *Long Island.*

Optical Faraday Rotation and Microwave Interactions in Paramagnetic Salts

William S. C. Chang and James Q. Burgess

The paramagnetic optical Faraday rotation is the averaged property of all the energy states of the paramagnetic ion. Therefore, any perturbation of the population distribution of the energy states caused by the microwave power absorption would manifest itself as the interaction between the optical Faraday rotation and the microwave radiation. A general calculation of this effect, plus some experimental results, are presented in this paper. An attempt is made to analyze the behavior and to evaluate the applications as optical modulators, detectors, and relaxation measuring devices.

I. Introduction

The magnetic Faraday effect (i.e., the rotation of the plane of polarization of light passing through a single crystal along its optical axis under the influence of the dc magnetic field) is very large, in general, in paramagnetic salts. Measurement and analysis of these rotations have been reported by various workers since Faraday's time.[1,2,3,4] However, the interaction of the Faraday rotation with the microwave resonance absorption has only been investigated[5,6,7,8,9] recently. The major stimulant of the recent research activities on the Faraday rotation comes from its applications in lasers and masers. For example, the Faraday rotation has been proposed to provide microwave modulation to the optical laser light beam. It provides also an optical means of measuring the relaxation processes of population densities in infrared and microwave masers. It can be used to detect infrared and microwave radiations.

It is the purpose of this paper to discuss this interaction, in general, and its applications as detectors, modulators, and relaxation measuring devices.

II. The Optical Faraday Rotation in Paramagnetic Salts

Macroscopically the Faraday rotation can be described as [1]

$$\theta = A \tanh \frac{\mu H_a}{kT} + BH_a, \tag{1}$$

where H_a is the effective applied magnetic field; T is the temperature; μ is the magnetic moment; k is the Boltzman's constant; and θ is the Faraday rotation in degrees per millimeter of optical path length. The first term represents the paramagnetic Faraday rotation effect while the second term is the diamagnetic Faraday rotation. At liquid helium temperature, only the ground Zeeman states are populated. Thus the T can be replaced by the spin temperature, T_s, of the paramagnetic ground states.* Furthermore, in most paramagnetic samples at $1.6°K \leq T \leq 4.2°K$, $\mu H_a \ll kT$ and $A \tanh (\mu H_a/kT) \gg BH_a$. Hence,

$$\theta \sim A \frac{\mu H_a}{kT_s}, \tag{2}$$

$$\frac{d\theta}{\theta} \sim -\frac{dT_s}{T_s}. \tag{3}$$

When moderate microwave resonant absorption occurs, the radiation energy tends to heat up the resonance energy states. Therefore, the change in Faraday rotation can be described primarily as the change in spin temperatures. This description is strictly valid only for two-level paramagnetic ions. For multilevel systems, different pairs of energy levels would have different spin temperatures. Consequently T_s must be replaced by the weighted average of the T_s between all the pairs of levels.

Consider the case of a $S = 1/2$ paramagnetic material placed inside a cavity with P_{in} amount of microwave power input. T_s can be solved according to the maser rate equations as follows[10]:

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* One defines the T_s by equating $\exp[(E_1 - E_2)/kT_s]$ to the ratio of the population of the state E_2 to the population of the state E_1.

$$n_1\omega_{12} - n_2\omega_{21} + (n_1 - n_2)\,\bar{W} = \frac{dn_2}{dt}, \tag{4}$$

$$-n_1\omega_{12} + n_2\omega_{21} + (n_2 - n_1)\,\bar{W} = \frac{dn_1}{dt}, \tag{5}$$

$$\omega_{12} = \omega_{21} \exp\,[(E_2 - E_1)/kT_b], \tag{6}$$

where ω_{12} is the spin lattice relaxation rates from E_1 level to E_2 level; $\bar{W}$ is the induced transition probability; T_b is the bath temperature; and n_2 and n_1 are the populations of the states E_1 and E_2. The solutions of Eqs. (4)–(6) for a steady-state condition (i.e., $dn_i/dt = 0$) is

$$T_s = T_b \frac{W + \omega_{12}}{\omega_{12}}. \tag{7}$$

From microwave analysis, one obtains

$$\bar{W} = \frac{P_{abs}}{(n_2 - n_1)\mu H_a}, \tag{8}$$

$$P_{abs} = P_{in} \frac{4\beta}{(1 + \beta)^2}. \tag{9}$$

Here, the cavity magnetic absorption is assumed to be much larger than its ohmic loss. β is the coupling coefficient of the cavity ($\beta = Q_0/Q_{ext}$), and P_{abs} is the power absorption of the paramagnetic sample. Therefore, the change in Faraday rotation, $\Delta\theta$, caused by the microwave power absorption can be written as

$$\frac{\Delta\theta}{\theta^0} = -\frac{4\beta\, P_{in}}{\omega_{12}(n_2 - n_1)\mu H_a(1 + \beta)^2}. \tag{10}$$

where θ^0 is the Faraday rotation at thermal equilibrium.

This macroscopic analysis gives a fairly good description of the interactions between the Faraday rotations and the moderate microwave resonance absorption for c.w. or amplitude modulated microwave input with the modulation frequencies much slower than the spin lattice relaxation rates. For strong microwave radiations, or any crystal having effective spin angular momentum greater than $^1/_2$, one must use the microscopic expressions to analyze the interaction.

Microscopically, the macroscopic dielectric property of any material is determined by the statistically averaged electric polarization vector $\langle\bar{\mathbf{P}}\rangle$ induced by the electric field of the incident electromagnetic radiation.[11] Rosenfeld and Van Vleck have calculated in detail the Faraday rotation without microwave radiation using the microscopic approach.[2,3,12] Their results give

$$\theta = \frac{l\pi}{\lambda n_\perp} \sum_{m,\,n} \frac{-j\omega_p[(p_x)_{nm}(p_y)_{mn} - (p_x)_{mn}(p_y)_{nm}]}{\hbar[\omega_p^2 - \omega_{mn}^2]}\,\rho_{mm}, \tag{11}$$

where $n_\perp$ is the index of refraction perpendicular to the path; λ and ω_p are the wavelength and angular frequency of the optical radiation; l is the optical path length; the direction of propagation of optical radiation is taken to be the z direction; $(p_x)_{nm}$ and $(p_y)_{nm}$ are the matrix element of the electric dipole moment in the x and y directions; and ρ_{mm} is the population of the state m (i.e., it is the diagonal density matrix element times the number of atoms per unit volume). When one takes into account the fact that, at the low temperatures, only the Zeeman levels are significantly populated, the Faraday rotation can be divided into the usual paramagnetic and diamagnetic terms similar to Eq. (1), for the optical wavelength region in which the energy of the photon is much larger than the splitting of the multiplets. Notice the important feature of the microscopic result that the θ is proportional to the weighted average of the population densities.

In 1953 Opechowski[6] extended the microscopic analysis to include the efforts of moderate c.w. microwave radiation assuming that all the energy levels have a single relaxation time. For amplitude modulated or pulsed microwave radiation, the microscopic analysis of the microwave radiation effects can be carried out on the perturbation basis where the primary effect of microwave radiation is considered as the change of ρ_{mm} from their thermal equilibrium values.[13] This approach is valid as long as the optical radiation is weak enough not to introduce optical pumping effects and the cross product terms of microwave and optical radiation can be neglected. Several interesting results were obtained from such a perturbation analysis.[13]

(a) From the rate equation analysis of the population densities of the Zeeman levels,[10] one can show that the Faraday rotation would always be directly proportional to the weak resonant microwave power incident upon the sample. This result is valid for a multilevel paramagnetic substance as well as the two-level systems.

(b) Since there are well-known microwave paramagnetic resonance techniques such as 180° pulse, adiabatic fast passage, and population inversions[14–20] to modulate the population densities of these Zeeman levels,[16,17,19] very intriguing time dependence patterns of Faraday rotation can be obtained.

(c) Since the Faraday rotation is proportional to the weighted average of the population densities of all the lowest Zeeman levels, the measurement of the relaxation of the Faraday rotation to its thermal equilibrium value after the microwave radiation is turned off indicates the averaged relaxation rates of the Zeeman levels that are affected by the microwave radiation.

On the other hand, Bloembergen *et al.*[9] have shown theoretically that for a microwave field of saturating strength, but smaller than line width, the dispersive components of the magnetization do not saturate.[16] Therefore, if this rf magnetic field is placed along the direction of the optical light (i.e., H_{rf} is parallel to z) a θ_p modulated at the microwave frequency would occur.

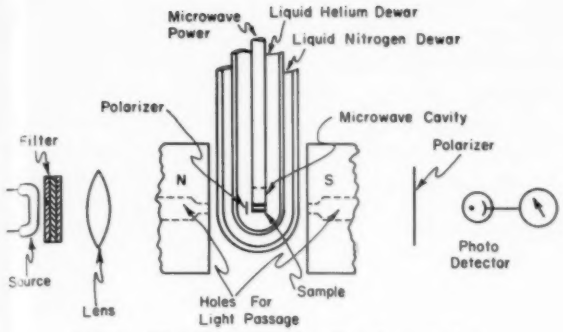

Fig. 1. The detection of the Faraday rotation.

III. Applications and Experimental Results

A. Spin-Lattice Relaxation Measurement

From Eq. (11), it is obvious that θ_p is always proportional to ρ_{mm}. Therefore, if one regards the microwave radiation as a perturbation to change the ρ_{mm} values, the relaxation of θ_p to θ_p^0 indicates the relaxation of the ground states population to their thermal equilibrium distribution. Figure 1 shows the physical arrangement through which the relaxation rate of the averaged spin temperatures can be measured by means of the θ_p. This type of measurement is quite different from the usual microwave relaxation measurement which monitors only one pair of energy levels. Comparison of these data with the usual paramagnetic relaxation results offers very valuable extra information on the relaxation process. Daniels and his co-workers have used this method in the measurement of spin-lattice relaxation of Nd $(C_2H_5SO_4)_3$. However, they have a two-level system; hence their results are the same as what would have been obtained by the normal microwave methods. We have measured the relaxation of θ_p after a moderate microwave pulse on a sample of dark ruby (1.5%Cr^{+++} in Al_2O_3).

The relaxation time was found to be 150 msec which is several orders of magnitude slower than the values obtained from the electron paramagnetic resonance techniques. The explanation is that the spin-spin interaction is strong enough so that all the spin systems reached a quasi-equilibrium state among themselves before relaxing back to the bath temperature. The 150 msec represents the true spin-lattice relaxation time. Notice that this value agrees with the spin-lattice relaxation times occurring in pink ruby (0.05% concentration). It follows that the maser action in concentrated materials may not be hampered by the fast spin-lattice relaxation rates but rather by the fast spin-spin processes.

If the 180° pulse or the adiabatic fast passage is performed in the paramagnetic sample the measurement of θ_p would reveal the relaxation of one pair of energy levels only. This technique can also be extended to infrared frequencies to take advantage of the fast time constant offered by the photomultipliers not available in many infrared detectors.

B. Radiation Detection

Since θ_p is also proportional to W (i.e., the induced transition probability) it follows that the $\Delta\theta_p$ caused by the microwave absorption also measures the radiation power incident upon the sample. A crude version of the Faraday detector is already shown in Fig. 1. Like all the proposed quantum counters, such a detector immersed in the liquid helium bath will produce very little noise in $\Delta\theta_p$ because of the low temperature involved and the absence of the spontaneous emission noise.[20] Theoretically, if the infinitesimal amount of $\Delta\theta_p$ can be measured, the effect of each photon of radiation would be measurable. But in practice, one is limited by the minimum detectable value of $\Delta\theta_p$ in the optical system.

Assume that, for a practical detector, $(E_2 - E_1)/h = 10^{10}$ cps, $T_1 \cong 100$ msec, and $N = 10^{18}$/spins. Then, from the results derived in Section II, one obtains

$$\frac{\Delta\theta_p}{\theta_p^0} \cong P \times 10^3, \tag{12}$$

where P is the microwave power in watts. Figure 2 shows the measured Faraday rotation angle θ_p as a function of the dc magnetic field for H_{dc} parallel to z. No substantial amount of Faraday rotation has been measured for the dc magnetic field perpendicular to the z axis. Assuming that $\theta^0 = 100°$ for a sample 1 cm long, and that $(\Delta\theta_p)_{min} = 0.01°$ for a photodetector and analyzer set, the minimum detectable signal is

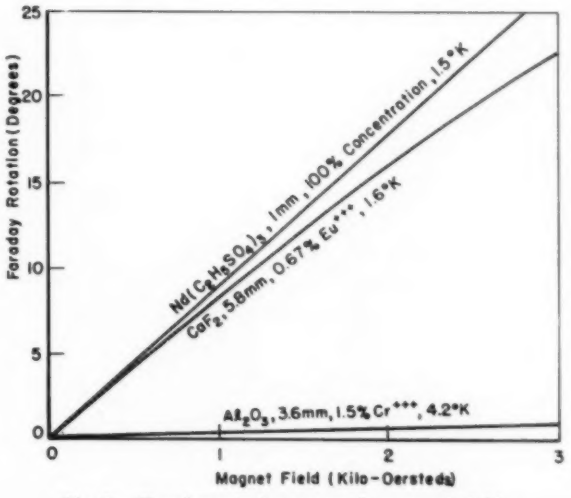

Fig. 2. Faraday rotation versus dc magnetic field.

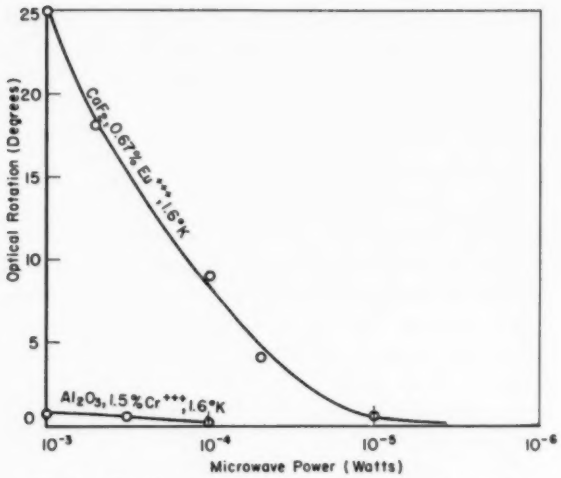

Fig. 3. Faraday rotation versus c.w. microwave power.

10^{-7} watts. Figure 3 shows the measured $\Delta\theta_p$ as a function of the microwave power input for a piece of CaF_2, doped with Eu^{+++}, 5.8 mm long.

To improve this sensitivity, one can obviously coat the ends of the sample with two highly reflecting films similar to the Fabry-Perot interferometer. The multiple reflections would increase significantly the total averaged value of θ_p^0. Sample calculations assuming an incoherent light beam indicated that an increase of θ_p^0 by two to three orders of magnitude is possible.[8] Taking into consideration the possible decrease in the transverse dimensions of the sample and the use of more optimum doping and concentration, it appears that a practical sensitivity of 10^{-10} to 10^{-11} watts, based upon the present available techniques, is obtainable. Higher sensitivities can only be obtained by means of future development in double beam interferometric techniques using the coherent stable laser itself as the light source to obtain a much smaller value of $\Delta\theta_{min}$.

Many conventional microwave detectors have a sensitivity much higher than 10^{-10} watts. Therefore, the Faraday detector will not be considered as an ultrasensitive detector for microwave radiation within its present sensitivity limit. However, since the resonance absorption lines of these materials exist in far-infrared

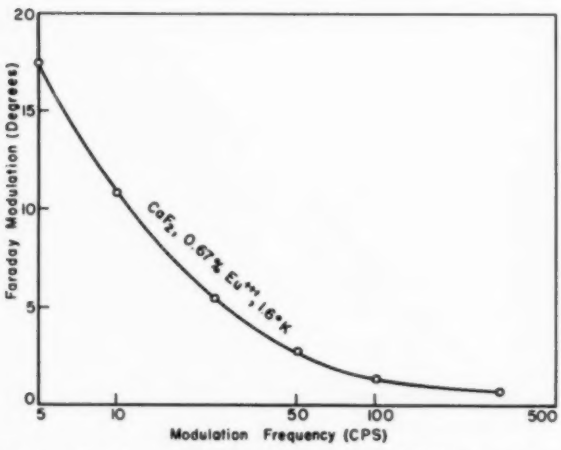

Fig. 4. Faraday modulation depth versus modulation frequency.

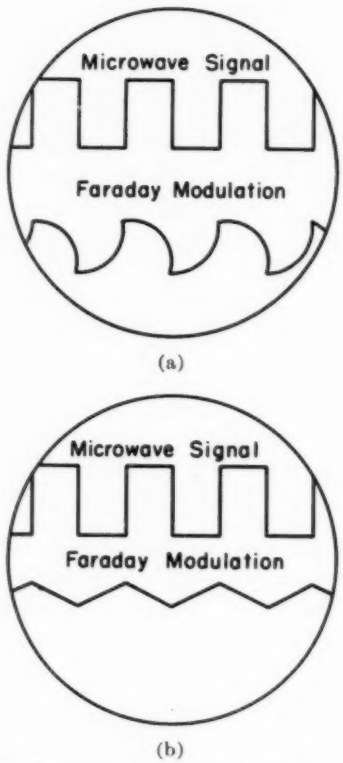

Fig. 5. Faraday modulation distortion at $f_m > 1/T_1$. (a) Microwave modulated at 5 cps. (b) Microwave modulated at 100 cps.

wavelength also, this detector principle is applicable as a narrow band, tunable, far-infrared detector which is quite unique.

C. Modulation of Optical Light

When a polarizer is placed behind the emergent linearly polarized light from the paramagnetic sample, the $\Delta\theta_p$ produced by the microwave radiation can be utilized to amplitude-modulate the light beam. Since this problem is so important to the application of the lasers, a great deal of interest has been generated in using the Faraday rotation as a modulator.

The simplest means of modulating the optical light by the Faraday effect is to amplitude-modulate the microwave resonance power. Since 100 degrees of θ_p are available, 100% depth of modulation would be achievable. However, unless the modulation frequency is much slower than the spin-lattice relaxation time, the distortion of the modulation shape as well as the decrease of modulation depth would occur. Figures 4 and 5 show the modulation effects of CaF_2 doped with Eu^{+++} ion as a function of frequency. Notice that this sample has a spin-lattice relaxation time of 200 msec. Therefore, modulation distortion occurs even at 5 cps. This is, of course, almost an extreme case because there are many paramagnetic materials having approximately 1 msec relaxation time.

For pulsed lasers, large modulation depth and high modulation frequencies can be achieved using pulsed high power microwave radiation at the resonance frequency of the energy levels to create the precessing motions of the population densities similar to the 180° pulse in electron paramagnetic resonance. In this case, the modulation frequency is limited by the microwave power available and the thermal heating of the sample.

The most sophisticated modulation method is suggested by Bloembergen *et al.*[9] Here, the θ_p is produced essentially by the dispersive components of the dielectric tensor of the strong microwave field at a frequency slightly off the resonance. Modulations up to the microwave frequency range can be obtained. However, the depth of modulation is extremely limited due to the smallness of the magnitude of the H_{rt}. In fact, the theoretically estimated $\Delta\theta_p$ is hardly detectable. Therefore, this method probably will not be useful as a modulator.

The idea of using the Faraday rotation as a detector was first considered with A. E. Siegman when one of the authors (W. S. C. Chang) was at Stanford University. The initial theoretical studies were partially supported by a NASA Grant. The authors also wish to thank R. E. Whitacre for his assistance in obtaining some of the experimental data.

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photo D. L. MacAdam

Four OSA members at the Los Angeles October 1961 meeting: J. R. Meyer-Arendt *Utah,* A. Lohmann *Braunschweig (presently with IBM),* W. Striker *Baird,* and H. G. Eldering *Baird.*

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0.01, and a nomogram for the calculation of molar refractions. The literature cited in the text includes 459 references.

Several shortcomings detract from the book which, on the whole, is effectively printed, excepting the regrettable absence of an index. At least a dozen minor typographical errors were noted in the text, and orthography of several Western authors has suffered in the transliteration from the Russian. Retention of the Russian letter э as a general symbol for an atom or ion, and designation of the number of negative charges of an ion by apostrophes are confusing variants when juxtaposed to accepted nomenclature. Finally, the headings of several tables could be more explicit in their definition of the tabulated quantities.

KARL H. ILLINGER

The Structure of Glass, Vol. 2. Proceedings of the Third All-Union Conference on the Glassy State, Leningrad, November 1959. Translation published by Consultants Bureau, New York, 1960. $25.00.

This report of the 1959 conference contains about 100 papers, many presented in condensed form, which describe Russian work on the structure of glass since the previous conference in 1933. Of special note is the fact that this translation was published in the U.S.A. simultaneously with the original publication in Russian, a noteworthy and welcome example of cooperation. In addition to the papers there is a comprehensive report of the discussions.

The contributions under the heading "Optical Properties and the Structure of Glass" include a series of papers from Florinskaya and others on the study of glasses in the Na_2O-SiO_2 system and their devitrification products by the methods of infrared reflection spectra, Raman spectra, and x-ray diffraction. The authors interpret the results in terms of the crystallite theory of glasses and their interpretation is severely criticized by Gross. It is also claimed that unidentified devitrification products have been observed which do not correspond to any known form of silica or a sodium silicate.

An interesting paper by Siderov *et al.* discusses the infrared absorption and Raman spectra of B_2O_3 glass; the Raman spectrum contains eight frequencies and the absorption spectrum three bands, from which it is deduced from considerations of symmetry that B_4O_6 molecules must exist in the glass. These molecules are also claimed to exist in lead borate glasses but this argument is not very convincing.

A group of papers on the "Electrical Properties of Glass" includes an analysis by Myuller in terms of Frenkel's theory of conduction in ionic crystals which leads to the conclusion that caesium ions exist in pairs in borate glasses. Other papers deal with the properties of BaO-Al_2O-B_2O_3-SiO_2 and Na_2O-Al_2O_3-SiO_2 glass. There are also short papers on electrode glasses for the determination of alkali ion activities. Of particular note is the number of papers on semiconducting glasses; these are mostly concerned with mixtures of sulfur, selenium, tellurium, arsenic, and antimony but there is also a short paper on glasses containing V_2O_5.

More general topics touched upon include delayed elasticity in fibers, radiation damage, variation of elastic modulus with temperature segregation in borosilicate glasses, and the properties of alumino-borosilicate glasses.

Much of the discussion centered around the question whether glass contains crystallites. At times one had the impression that, at all cost, the results were to be interpreted in terms of crystallites; however, there are outspoken critics of this theory and there are others, trying to seek a compromise, who suggest the presence of smaller and smaller crystallites joined by regions of random, or disordered, arrangement. There is a complete absence of any recognition of the importance of transformation range phenomena, and little attempt at a comprehensive view of the problem. Nevertheless the discussion is worth reading if only for the purpose of revealing the state of thinking on the subject in the U.S.S.R. There are clearly some very capable scientists interested in the field there and also some whose background appears to be inadequate to support them in this kind of discussion. The gulf between the physicist and the technologist is commented on by Kitaigorodskii in his concluding remarks. One delegate complained that "a discussion of problems of the glassy state gives nothing to industrial workers." This may strike some readers as a not entirely original observation. The conference does give a most impressive picture of the glass industry in Russia in both the number of delegates present and the mass of experimental work reported. The translation is certainly to be valued and will, in some direction or another, be found stimulating to anyone interested in the field.

R. W. DOUGLAS

Tables of Blackbody Radiation Functions. By M. PIVOVONSKY and M. R. NAGEL. Macmillan, New York, 1961. 481 pp. $12.50.

How does one review a book consisting of 42 pages of introductory text followed by 481 pages of closely spaced numerical tables?

Dr. Nagel, the senior author, explains that he began the compilation as a subordinate phase of a wartime project concerned with the development of artificial light sources for photographic, photometric, and colorimetric research. The work disclosed a need for blackbody radiation data of a higher degree of precision than was available at the time. For greatest efficiency, the tables were computed with the wavelength and temperature intervals spaced closely to minimize interpolation errors. Further, to minimize the obsolescence consequent on the inevitable revisions of the basic constants of radiation theory, a set of supplementary correction tables have been added.

The two time constants of Planck's equation, c_1 and c_2, have been assigned the values 1.1909×10^{-12} cm² watt sterad^{-1} and 1.4380 cm °K, respectively. The freezing point of platinum is taken as 2042°K. A detailed preface carefully reviews the terminology of the basic radiation functions and defines the equations of blackbody radiation. A number of the relations developed here are suggestive of those discussed by Makowski and embodied in the Thornton radiation slide rule (Rev. Sci. Instr. **20,** 876 (1945)). This will be discussed later.

Table I is a tabulation of: (1) the spectral radiance of a blackbody in terms of wavelength and temperature, (2) the ratio of the radiance at a stated temperature and wavelength with the radiance at the same temperature at 560 mμ, and (3) the fraction of the total energy emitted by a blackbody in the spectral band between $\lambda = 0$ and the tabulated wavelength. These functions are tabulated to five significant figures for values of λ between 200 and 590 mμ in 5 mμ intervals and between 590 and 1200 mμ in 10 mμ intervals at temperatures between 800 and 40,000°K, in temperature intervals which are varied to match best the needs of each temperature range. Data are interpolated for a number of intermediate temperatures of especial interest.

Table II is a continuation of Table I for wavelengths between

continued on page 342

Optical and Cross Relaxation Maser Level Populations by Partial Distribution

W. A. Barker and J. D. Keating

The method of partial distributions is used to calculate the population distribution of three level maser systems in which spontaneous emission and cross relaxation as well as thermal relaxation and induced absorption processes are included. The results obtained are in agreement with the solution of the relevant rate equations. The method has the advantage of speed and suggestiveness. Two examples are presented: (1) A three level optical maser is analyzed in which one spontaneous emission transition probability is included. The solution in this example does not make the linear approximation to the Boltzmann factor. (2) A three level microwave maser is analyzed in which one cross relaxation mechanism is included. The solution to this problem by the method of partial distributions does require use of the linear approximation to the Boltzmann factor.

I. Introduction

The method of partial distributions was recently described in a paper by Keating *et al.*[1] It is essentially a computational technique for obtaining the energy level populations in a maser system. The results obtained by this method agree with those obtained in the conventional solution of the rate equations. The advantages of the method are twofold:

1. It is fast, and thus enables one to treat multilevel systems in which there are numerous transitions connecting the states.

2. It is suggestive, and thus enables one to gain some physical insight into the mechanisms which aid or hinder maser action.

In its initial formulation[1] the method was applied to cases in which the states were connected by thermal relaxations and radiative induced transitions. The present paper extends the method to apply to the calculation of maser level populations in which spontaneous emission or cross relaxation is significant. Two examples are presented. The first treats a three level optical maser or laser,[2] and the second a three level microwave maser in which one cross relaxation[3] has an appreciable transition probability.

II. Spontaneous Emission

Consider the three level system of Fig. 1. An optical pump is applied between levels 1 and 3. In addition to $W_{31} = W_{13}$, which denotes the radiative induced transition probability, we assume that A_{21} is the only significant spontaneous emission transition probability and that $w_{32} = w_{23}\, e^{\delta}$ is the dominant thermal relaxation transition probability. In the optical range, unlike the microwave range, it is not permissible to use the linear approximation for the Boltzmann factor, as $\delta = h\nu_{32}/kt$ and $\Delta = h\nu_{21}/kt$ are not small in comparison to unity. The solutions we seek are the normalized populations n_1, n_2, and n_3.

The three relevant partial distributions are indicated in Figs. 2–4. ρ_i^k represents the relative population of the ith level in the kth partial distribution. Each of the

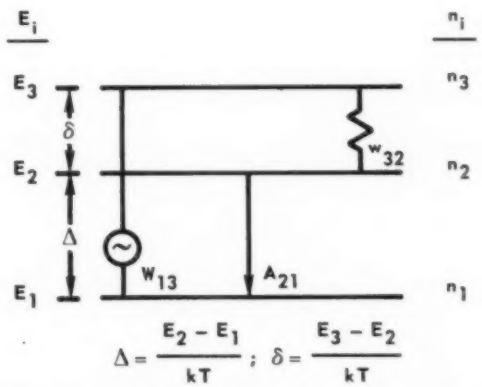

Fig. 1. Spontaneous emission in a three level optical maser.

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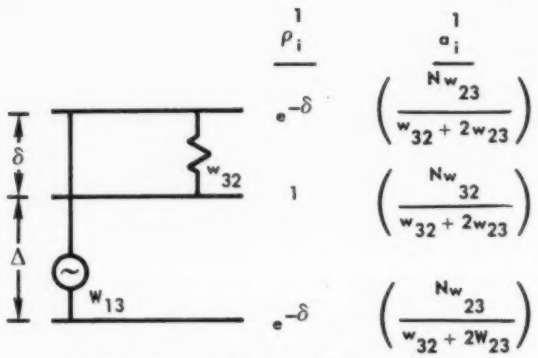

Fig. 2. Partial distribution due to W_{13} and w_{32}.

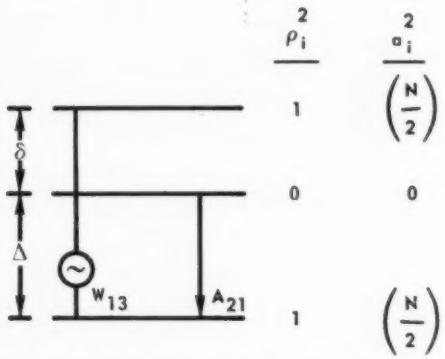

Fig. 3. Partial distribution due to W_{13} and A_{21}.

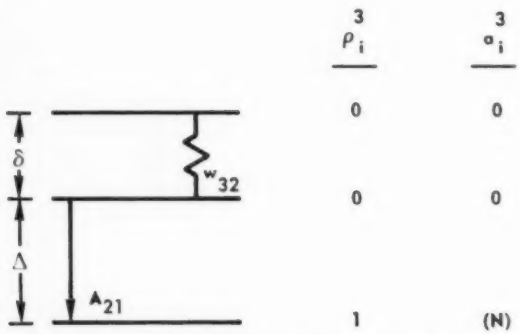

Fig. 4. Partial distribution due to w_{32} and A_{21}.

ρ_i^k may be readily found in a given partial distribution by using the following simple rules:

1. The induced radiative transition probability W_{13} is an "equalizer," i.e.,

$$\rho_1^k = \rho_3^k \qquad \text{for } k = 1, 2. \tag{1}$$

2. The thermal relaxation transition probability w_{32} is a "thermalizer," e.g.,

$$\frac{\rho_2^1}{\rho_3^1} = e^{\delta} = \frac{w_{32}}{w_{23}}. \tag{2}$$

w_{32} connects levels 2 and 3 in the first partial distribution.

3. The spontaneous emission probability A_{21} is a "depleter." It empties the upper level to which it is connected. Thus,

$$\rho_2^2 = \rho_2^3 = 0. \tag{3}$$

a_i^k represents the normalized population of the ith level for the kth partial distribution.

$$a_i^k = \frac{N\rho_i^k}{\sum_i \rho_i^k}. \tag{4}$$

f_k is a weighting factor which represents the probability of the kth partial distribution.

The prescription for computing the f_k is quite simple:

$$f_k = \frac{X_k \sum_i \rho_i^k}{\sum_{i,k} X_k \rho_i^k}. \tag{5}$$

where X_k is the product of the transition probabilities responsible for the kth partial distribution. Hence

$$f_1 = \frac{W_{13}(w_{32}+2w_{23})}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{21}+w_{32}A_{21}},$$

$$f_2 = \frac{2W_{13}A_{21}}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{12}+w_{32}A_{21}}, \tag{6}$$

$$f_3 = \frac{w_{32}A_{21}}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{21}+w_{32}A_{21}}.$$

Each of the n_i may be found as follows:

$$n_i = \sum_k a_i^k f_k. \tag{7}$$

Hence

$$n_1 = N\left[\frac{W_{13}(w_{23}+A_{21})+w_{32}A_{21}}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{21}+w_{32}A_{21}}\right],$$

$$n_2 = N\left[\frac{W_{13}w_{32}}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{21}+w_{32}A_{21}}\right], \tag{8}$$

$$n_3 = N\left[\frac{W_{13}(w_{23}+A_{21})}{W_{13}(w_{32}+2w_{23})+2W_{13}A_{21}+w_{32}A_{21}}\right].$$

It is easily seen that the n_1 so constructed satisfies the normalization equation

$$n_1 + n_2 + n_3 = N \tag{9}$$

and the rate equations

$$\frac{dn_1}{dt} = -n_1W_{13} + n_3W_{31} + n_2A_{21} = 0,$$

$$\frac{dn_2}{dt} = -n_2A_{21} - n_2w_{23} + n_3w_{32} = 0, \tag{10}$$

$$\frac{dn_3}{dt} = -n_3W_{31} + n_1W_{13} - n_3w_{32} + n_2w_{23} = 0.$$

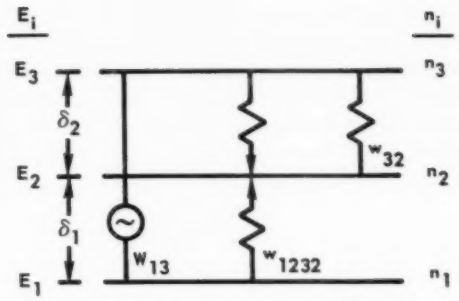

Fig. 5. Cross relaxation in a three-level microwave maser.

III. Cross Relaxation

Consider the three level system of Fig. 5. A microwave pump is applied between levels 1 and 3. $W_{31} = W_{13}$ represents the radiation induced transition probability. We assume that $\nu_{12} \approx \nu_{32}$ so that w_{1232} is the only significant cross relaxation transition probability. For simplicity we take $w_{32} = w_{23}e^{\delta_2}$ as the dominant thermal relaxation transition probability, and assume complete saturation: $W_{13} >> w_{32}, w_{1232}$.

The rate equations for this case may not be solved immediately by the method of partial distributions for the reason that cross relaxation introduces terms quadratic in the n_i. However, in the microwave range the linear approximation to the Boltzmann factor may be used except at very low temperatures. Consequently, by assuming that each of the n_i does not differ very much from $N/3$, the rate equations may be put in a form suitable for treatment by the partial distribution method.

The rate equations and normalization equation are:

$$\begin{aligned}
\frac{dn_1}{dt} &= -n_1W_{13} + n_3W_{31} - \frac{W_{1232}}{N}(n_1n_3 - n_2^2) = 0,\\
\frac{dn_2}{dt} &= -\frac{w_{2123}}{N}(n_2^2 - n_1n_3) + n_3w_{32} - n_2w_{23} = 0,\\
\frac{dn_3}{dt} &= -n_3W_{31} + n_1W_{13} + n_2w_{24} - n_3w_{32}\\
&\qquad - \frac{w_{3212}}{N}(n_1n_3 - n_2^2) = 0,\\
n_1 + n_2 + n_3 &= N,
\end{aligned} \tag{11}$$

where $w_{1232} = w_{3212} = w_{2123}/2$. In the limit of complete saturation $n_1 = n_3$ and we need to linearize only the second of Eqs. (11).

$$\begin{aligned}
\frac{dn_2}{dt} &= -\frac{2w_{1232}}{N}(n_2 - n_1)(n_2 + n_1) + n_1w_{32} - n_2w_{23}\\
&\approx -\frac{4}{3}w_{1232}(n_2 - n_1) + n_1w_{32} - n_2w_{23} = 0.
\end{aligned} \tag{12}$$

There are two relevant partial distributions and these are indicated in Figs. 6 and 7, respectively. The cross relaxation transition probability brings two spin systems into equilibrium with one another.

$$\frac{\rho_1^1}{\rho_2^1} = \frac{\rho_2^1}{\rho_3^1}. \tag{13}$$

As in the case of the optical maser W_{13} acts as an "equalizer" and w_{32} as a "thermalizer." The ρ_i^k and a_i^k are thus readily written down. The f_k may again be found using Eq. (5) with $X_1 = {}^4/_3\, w_{1232}W_{13}$ and $X_2 = w_{32}W_{13}$.

$$\begin{aligned}
f_1 &= \frac{4w_{1232}}{4w_{1232} + 3w_{32}},\\
f_2 &= \frac{3w_{32}}{4w_{1232} + 3w_{32}}.
\end{aligned} \tag{14}$$

And the n_1 may be obtained from Eq. (7)

$$\begin{aligned}
n_1 = n_3 &= \frac{N}{3}\left[1 - \frac{h\nu_{32}}{kt}\frac{w_{32}}{4w_{1232} + 3w_{32}}\right],\\
n_2 &= \frac{N}{3}\left[1 + \frac{2h\nu_{32}}{kt}\frac{w_{32}}{4w_{1232} + 3w_{32}}\right].
\end{aligned} \tag{15}$$

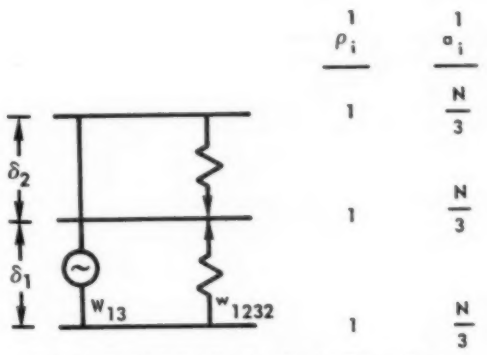

Fig. 6. Partial distribution due to W_{13} and w_{1232}.

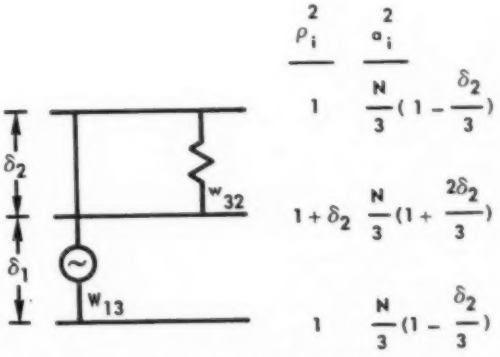

Fig. 7. Partial distribution due to W_{13} and w_{32}.

It is readily seen that the n_1 constructed in this fashion satisfies Eqs. (11) in the approximation considered.

IV. Conclusion

The method of partial distributions may be applied to multilevel maser systems in which thermal relaxations, radiation induced transitions, spontaneous emission, and cross relaxation are important. The treatment of spontaneous emission represents an extension of the earlier work to cases where $h\nu/kt$ is not necessarily small. The treatment of cross relaxation is limited to cases in which the relevant rate equations may be linearized. The two simple cases discussed in this paper demonstrate the method and indicate some important physical features of each system. It is clear from Figs. 2–4, 6, and 7 that maser operation is aided in each case by a fast thermal relaxation. The three level optical maser is impeded by fast spontaneous emission and the three level microwave maser is impeded by fast cross relaxation. The computational advantage of the method of partial distributions has not been demonstrated in the treatment of these two simple three level cases where clearly a straightforward solution of the relevant rate equations may be used to obtain the normalized population distribution. However, we have treated more complex systems, e.g., one involving 84 partial distributions, and have found that the technique described is a great time saver.

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High-Speed Sequence Photography of a Ruby Laser

E. S. Dayhoff and B. Kessler

The sequence of phenomena occurring when a ruby laser crystal is flashed is studied on a microsecond time scale by means of a high-speed framing camera making about 500,000 frames per second. Two runs of photographs are presented. The individual bursts of light constituting the laser flash show the following characteristics: Each burst involves the whole active volume of the crystal; each burst shows a grainy or flocculated distribution of light across the face of the crystal, and this distribution changes in fine detail from frame to frame; the grains of brightness are often arranged in stripes and bands in patterns which change from frame to frame; there are some permanently dark regions; there are some pinholes in the silver coating which scatter an appreciable amount of light out of the main beam.

Introduction

The light emitted by oscillating ruby lasers is widely known to occur in a series of short bursts of a few microseconds duration. The whole train of such bursts may typically occupy an interval of time of 50 to 200 μsec each time the ruby is pumped above its threshold. Each burst of light presumably represents oscillation in one mode or one class of modes of whatever type may be available for the electromagnetic oscillations of the laser crystal.[1] In order to study the modes of oscillation and the mechanism of oscillation initiation, it therefore appears necessary to observe the individual bursts of light in their natural sequence.

Camera

The camera used by us to make sequential observations of the light bursts is a Beckman-Whitley Model 192 Framing Camera.[2] It records a strip of 80 independent exposures in each operation. Since it runs continuously it will make multiple exposures if the duration of the illumination is greater than the time required to make 80 exposures. Shuttering of individual frames is accomplished by means of a turbine driven rotating mirror in conjunction with several other optical elements. The framing rate may be varied over wide ranges by adjusting the air pressure supplied to the turbine. Speeds of 500,000 frames per second are easily obtained using compressed air to drive the turbine, while higher speeds are available when helium gas is used. Focusing of the camera is limited to the range from about 2 meters to infinity but auxiliary lenses will extend this range. The entrance pupil is split, each half being used for 40 frames of the 80 frame strip, and each pupil is in the shape of a narrow horizontal diamond, so it is necessary to use care in directing the laser beam into the camera to prevent vignetting by the edges of the entrance pupil.

The pictures shown in Figs. 1 and 2 were all made by photographing one oscillating ruby crystal in the following way: The camera was focused on the silvered end face of the crystal, though the accuracy of focusing was better for some runs than for others. The ruby crystal was aligned so that the spot of red light was thrown into one of the entrance pupils. When light was allowed to enter only one entrance pupil, only one-half of the resulting frames carry the impression of laser light, but there is no vignetting. The other set of 40 frames shows only a pattern of pinholes in the silvering, since light from pinhole sources is more divergent than the main laser beam and can enter both entrance pupils. Without an auxiliary lens the laser spot at the plane of the entrance pupil of the camera was about as large as the entrance pupil itself so it is difficult to guarantee a complete absence of vignetting, but when an auxiliary lens of 30.5 cm focal length was used the spot at the entrance pupil could be made about 1 cm in diameter, and it was a simple matter to insure that it was not clipped by the edge of the entrance pupil. The auxiliary lens was a 30.5 cm f.l. Aero Ektar $f/2.5$. Use of the auxiliary lens in-

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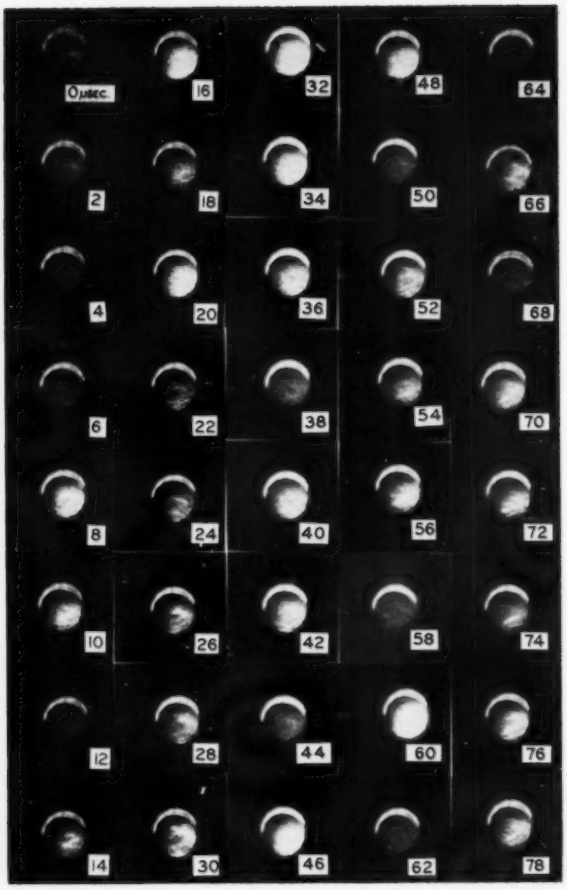

Fig. 1. End face of "Lasing" ruby. The ruby had shifted in its holder allowing a thin lune of pumping light to show at the top. The frames are labeled in microseconds but it is not known at which frame the flash begins. The camera was focused on the face of the ruby but focusing was somewhat imperfect. This flash was made with a pumping energy about 9% above threshold, crystal at room temperature, and with a silver coating of rather indifferent quality. No auxiliary lens was used and the original image was about 0.16 cm in diameter. Plus-X film.

creases the size of the image on the film (Kodak Plus-X) from about 0.16 cm diameter to about 1.3 cm. Since the laser beam is quite monochromatic and of small cross section, the geometric and chromatic aberrations of the lens should be negligible. The distance between the auxiliary lens and the crystal was such that off-axis rays would not cross the axis of the lenses.

Flash Head

Both photographs were taken with light from the same crystal. The crystal was an 0.05%–0.06% chromium doped ruby of laser grade supplied by the Linde Company. The pumping source was a General Electric FT 524 flashtube fed from a capacitor bank of 200 μf (for Fig. 1) and 300 μf (for Fig. 2) photoflash capacitors rated at 4000 volts. The crystal was shaped like a cylinder 5 cm long and 5 mm in diameter and was cut with the *c* axis of the crystal approximately parallel to the axis of the cylinder; an actual measurement with the back scattered x-ray technique indicated an error of about 1° in the parallelism of these axes. The sides were rough ground and the ends were polished flat and parallel to a limit of 1 minute of arc. The ends were vacuum coated with silver and overcoated with SiO. One end was opaque and the other had a transmission of roughly 0.3%.

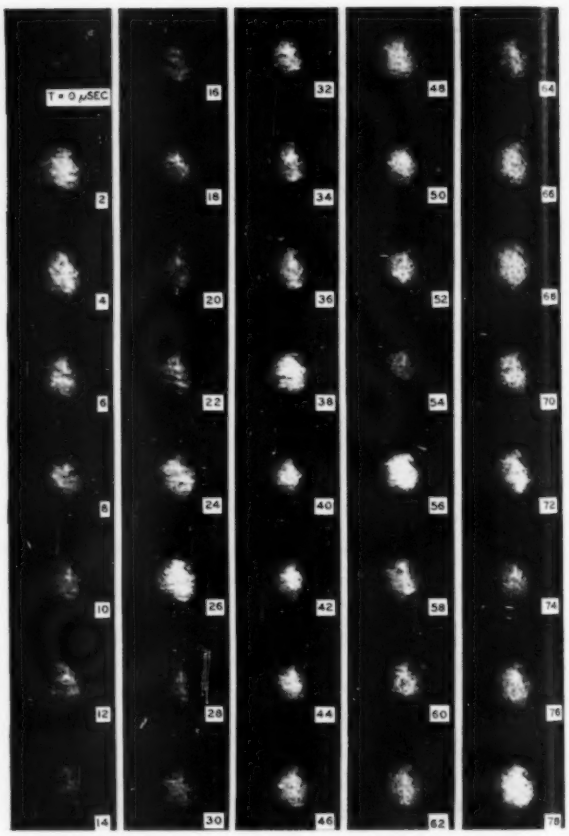

Fig. 2. End face of "Lasing" ruby. Frames labeled in microseconds with arbitrary zero. Camera better focused on ruby face than in Fig. 1. Pumping energy about 110% above threshold, crystal at room temperature, silver coating of good quality protected by layer of SiO which had probably oxidized to SiO_2. Aero Ektar auxiliary lens used providing an image on the film of about 1.3 cm diameter. Plus-X film.

Results

Some general characteristics may be recognized in the results. Individual bursts of light of duration of about a microsecond are seen and also others whose duration is of the order of 4 or 5 μsec. These are often separated by periods of almost complete extinction. A granular pattern of light is seen in each flash, and the pattern is seen to change in detail from flash to flash though it may be said in general that each flash occupies all of the active part of the crystal. (One crescent-shaped side of our crystal seems never to flash and hence is ignored as being inactive.) The patterns seen do not have any simple geometric configuration but do seem to have dark and light bands which move from frame to frame. In some cases there seems to be a sweeping motion, especially for the dark bands in Fig. 2. Figure 2, which is more accurately focused and less enlarged from the negative than Fig. 1, shows a number of bright pinholes which also appear in the mating 40 exposures made with the other entrance pupil. These pinholes remain in the same places from frame to frame and their brightness varies more or less with the laser flashing, suggesting that they are simply diffracting laser light into a spreading beam.

Discussion

A preliminary interpretation of these results may be attempted although much work remains to be done to verify these ideas. The inactive crescent shaped region of our crystal seems likely due to a departure from parallelism of the end faces along this side of the crystal due to a roundness of the ends. Certain other dark inactive areas may be due to polishing defects or other defects on the crystal. The generally grainy appearance of the light may result from a graininess of the deposited silver coat and, if so, should be different for crystals using multiple layer coatings of other materials. In certain frames (such as 60 μsec in Fig. 2) there seems to be an interference pattern in the grains. Other runs, not reproduced here, seem to confirm that patterns rather strongly suggestive of interference patterns will form under certain conditions.

Some interesting conclusions can be drawn from the general appearance of the pictures. The fact that each burst of light involves the whole active width of the crystal seems to indicate that, despite inhomogeneities in the crystal and irregularities in the polishing of the ends, the electromagnetic interaction responsible for the regenerative action links the whole crystal together from one side to the other, even though various properties such as angular spread of the beam suggest that coherence of the wave front is limited to a small fraction of the crystal area. (The angular spread observed for this crystal is about 0.5°.) One of our recent film strips not shown here provides some evidence that the wave front is rather uneven and irregular.

It is interesting to look for evidence of recognizable mode patterns. The unknown geometry variations of the end face of the crystal would probably so distort the mode patterns that they would become unrecognizable in detail. It is nevertheless possible that the patterns of bars in some frames are the result of individual modes or mixtures of modes of the better known types as they appear in the presence of distortions due to various imperfections. The bar patterns in Fig. 2 are particularly intriguing as they seem to have a growing and then a sweeping motion over a time interval of 5 μsec or so in a number of places.

Conclusion

It is apparent that the accumulation of additional data of this same general kind should do much to clarify the details of the laser process. Especially useful will be comparison studies on various crystals ground in different ways. The processes occurring in such crystals are obviously quite complex and must involve such things as switching and mixing of ordinary modes of a right circular cylinder at least.*

The authors wish to thank B. J. Crapo and T. Marshall for valuable assistance with the camera.

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* The authors feel it might well be useful for the word "LASER" to apply to devices in which these complex processes are important, as is generally the case with optical devices, and to use the word "MASER" in the apparently simpler case where the modes of oscillation are rather rigidly enforced by the apparatus, as is generally the case with microwave masers. Such usage would generally conform to current practice and assist in distinguishing certain physical processes which may otherwise require a new name.

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1.1 and 1000μ at temperatures between 20 and 13,000°K. These data are given to four figures.

Table III includes: (1) the relative spectral radiance referred to the maximum radiance at the indicated temperature, (2) a restatement of the wavelength ratios of Table I-2, and (3) an auxiliary function for computing the derivatives of the Planck function. These quantities are plotted for values of the function λT in the range of 0.01 to 0.99 cm °K. Procedures for evaluating the functions at higher values of λT are described in the text.

Table IV comprises the relations: (1) the total radiance of a blackbody, (2) the maximum radiance of a blackbody, and (3) the wavelength at which the maximum radiance occurs. All these quantities are given for temperatures from 1000 to 2500°K at 2° intervals, from 2500 to 5500°K at 5° intervals and from 5500 to 10,000°K at 10° intervals.

Table V is similar to Table III but with the quantities tabulated against wave numbers rather than wavelengths, and Table VI is similarly related to Table IV with the argument in reciprocal temperature units.

Table VII consists of two parts—a compilation of the luminance (photometric brightness) of a blackbody between 800 and 1796°K at 4° intervals and a table of the luminance and the three chromaticity coordinates in the temperature intervals of Table I.

Finally, Table VIII is an auxiliary temperature correction table to protect the tables against obsolescence with subsequent revision of the values of the physical constants.

Examples of the use of these tables are included in the book together with a collection of excellent bibliographies.

The magnitude of the effort contained in this magnificent compilation makes one hesitate before offering an adverse comment. This reviewer has found it necessary to interpolate to intermediate values of the temperatures in Tables I-3 and II-3. Using linear interpolation, as suggested in the preface, it was found that values midway between the tabulated temperatures were rarely accurate to more than three figures. The reviewer has no suggestion to offer other than the illogical suggestion that the tables be expanded still further. In general, the book will be an invaluable reference volume for people engaged in radiation, high-temperature, and spectroscopy work. Where considerable interpolation is needed, the radiation slide rule will be a useful adjunct.

S. KATZ

Tables of the Fractional Function for the Planck Radiation Law. By M. CZERNY AND A. WALTHER. Springer-Verlag, Berlin, 1961. 60 pp. 28DM

This book is about as short as the book of Pivavonsky and Nagel, reviewed above, is long. With it and a little study, however, one can perform certain calculations involving blackbody radiation functions that are not possible with the large volume. Every library should have both of these volumes, as together they present a very thorough treatment of the Planck radiation function.

Ten or fifteen years ago there existed only very limited tables of blackbody functions, and many of these tables were made using different values of the radiation law constants c_1 and c_2 from those generally accepted today. Parry Moon published tables in J. Opt. Soc. Am. **38,** 291 (1948) and A. N. Lowen and G. Blanch published tables in J. Opt. Soc. Am **30,** 70 (1940) (the so-called W.P.A. Tables) which this reviewer has found very useful in his work. Another handy short set of tables is contained in the book *Tables of Functions* by Jahnke and Emde, 4th ed., Dover Publications, New York (1945). The Second World War produced many engineering applications of infrared radiation and a renewed interest in blackbody functions. Prof. Czerny produced a "radiation slide rule" that was useful for quick calculations. M. W. Makowksi, while at the Polish Refugee College in London, designed a much more elaborate radiation slide rule [Rev. Sci. Instr. **20,** 876 (1945)] which is available commercially from A. G. Thornton, Ltd. (and various distributors). A. H. Canada, while at the General Electric Schenectady Laboratory, designed the G.E. slide rule which is usually found in every infrared man's briefcase. This is described in the *General Electric Review*, December 1948. While we are mentioning such handy aides for blackbody calculations we should mention another G.E. author, J. P. Chernoch, who published some nomograms in the July 1957 issue of *Aviation Age*, entitled "Infrared Calculations Made Simple." Here, by laying a rule across the temperature scale and wavelength scale, one can determine the percentage of the radiation of a blackbody at that temperature that falls below that wavelength. Another combination nomogram and slide rule has been recently described by Block Associates in their advertisement in J. Opt. Soc. Am. of January 1962.

For many engineering purposes small slide rules of this sort are completely adequate. Other uses began to arise in the post-war period which demanded higher accuracy. The simultaneous development of high-speed electronic computers made more precise calculation of the Planck function practical. The set of tables which Dr. Nagel had begun on a desk-type calculator at Darmstadt during the war was completed on a computer at the Harvard Computation Laboratory by Mark Pivavonsky and is described in the preceding review. The set of tables described here was also begun using a desk calculator but was completed in 1956 on an IBM 650 at the Institut für Praktische Mathematik (IPM) at the Technische Hochschule at Darmstadt. In 1959 A. G. DeBell of Rocketdyne Division, North American Aviation, needed an improved set of tables for some calculations he was making on flame temperatures, so he programmed an IBM 704 to make these calculations which are available as Rocketdyne Research Report 59-32. (Unfortunately he used a value 1.4388 for c_2, which is the most recent but not the generally accepted value.) In 1959 C. Ferriso of Convair, also making flame calculations, prepared a similar set of tables using an IBM 704. His tables however are in terms of intensity versus wavenumber rather than wavelength, so that they do fill a gap in the literature. In 1960 S. Twomey of the N.A.S.A. made a set of calculations for the blackbody function between 180°K and 315°K and between 3400 cm^{-1} and 20 cm^{-1}, which is more useful for meteorological calculations.

One is tempted to remark it is good that at long last detailed tables now exist for the Planck function, so that future users may be spared the trouble and expense of computing this function. This is not quite true, however; in this new modern world of 7090 super-high-speed computers, present-day workers simply program the function into whatever they are calculating. This is quicker for them than looking up the function in a table. So, we are lucky that these books have appeared; future scientists would have been too busy to tabulate these intermediate steps.

To discuss this book specifically, 20 of the 60 pages are devoted to a discussion of the Planck function. This book deals chiefly with the fractional functions of a blackbody radiator, that is, the ratio of the radiation between $\lambda_1 = 0$ and $\lambda_2 = \lambda$ to the total radiation of the blackbody radiator at that temperature (as

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Mode Control in Ruby Optical Masers by Means of Elastic Deformation

Morley S. Lipsett and M. W. P. Strandberg

A new technique has been applied in experimental work on ruby optical masers with dramatic results. The techniques involved elastically deforming the medium and thereby invoking the stress-optic effect. Strikingly, it permitted optimizing the elastic deformation of any particular ruby specimen to reduce significantly its pumping-energy requirements for the onset of maser oscillations. At the same time, the divergence of the emergent beam could be reduced by a sizable fraction to that characteristic of low-order radiation modes.

I. Introduction

The first announcement by Maiman[1] of the successful demonstration of optical maser action in pink ruby triggered an avalanche of interest in the scientific community. Rubies by the dozen were ground into cylinders, their ends were lapped to degrees of optical perfection, and their gross and most obvious properties were immediately studied by an equal number of investigators.[2–4] To everyone, however, it soon became evident that ruby optical masers, although tantalizingly simple in substance, give rise to enormously complicated phenomena.

With these phenomena in mind, the present study was undertaken with a dual objective. First, it was intended to elucidate the significance of some of the parameters influencing optical maser action in ruby. Second, it was intended to justify a conviction that, quantum mechanics notwithstanding, simple geometry is of prime importance in the operating characteristics of ruby optical masers.

In working toward these objectives a new experimental technique was used. The active medium was elastically deformed by means of transverse loading. This permitted, for the first time, the exercise of a large degree of control over the effective modes that give rise to the output radiation, and just as strikingly it permitted optimizing the elastic deformation of any particular ruby specimen to reduce significantly its pumping-energy requirements for the onset of maser oscillations.

The technique is evidently one that can be applied to any solid-state material for optical masers, and, of course, transverse loading is only one of the many ways of elastically deforming the material.

Roughly speaking, stressing can be thought of as a means of deforming the reflecting faces of an optical maser rod into parallelism. But it does so in a controlled way and separately along each of several degrees of freedom. In effect, it modifies the internal properties of the active medium so that the greatest possible volume can be encouraged to work into the lowest-order modes that the inhomogeneities of the medium can sustain.

In the typical case we are concerned with a ruby rod several centimeters long and some fraction of a centimeter in diameter. Its end faces are polished flat and parallel and are coated with partially transmitting metal or dielectric reflectors. The rod is surrounded by xenon flash lamps and subjected to a millisecond burst of intense white light. Population inversion takes place in the well-known way,[1] and stimulated emission of radiation builds up to the point where oscillations begin to produce coherent radiation. But the radiation that emerges from an end face of the rod is not spatially coherent in simple plane-wave fashion across the rod diameter. In the ideal case—a perfectly homogeneous active medium—this might be approximately the case. The active medium, however, is far from ideal. Even casual examination under

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polarized light of the best ruby available reveals myriads of strain lines, and other random variations in its index of refraction are not hard to detect. The oscillations, as a result, have to build up in only those higher-order modes that such an inhomogeneous medium can support. With the experimental results of the present study, the optical limitations of the medium can be more clearly defined.

The radiation emitted by a ruby optical maser can be characterized by its time development and by its spatial intensities at near and far fields. Detected photoelectrically and recorded with an oscilloscope, the time development is observed to be an aperiodic series of sharp, microsecond pulses beginning tens or hundreds of microseconds after excitation and lasting from one to several hundred microseconds, the duration depending on the properties of the xenon-flash pumping radiation. The series is least complicated near threshold where, in fact, it can be a small group of pulses, or even a single pulse. The spatial intensities can be photographed at the emitting face of the maser and at infinity for the near- and far-field patterns, respectively. The near-field patterns ordinarily tend to be topographical maps of the radiation modes, while the corresponding far-field patterns are more or less circular blurs characteristic of emergent beam divergence, typically of approximately one degree. It will be seen that, by means of the technique of elastic deformation, these properties can be influenced to a profound extent but in a systematic manner.

II. The Experiment

The Approach

Of the many conceivable parameters influencing optical maser action in ruby, the most likely limitation would be the material itself, for we have an optically inhomogeneous medium with both systematic and random variations in the index of refraction throughout its entire volume. In particular, the index of refraction across the diameter of a maser rod may have sizable gradients. Consider, therefore, a maser rod with perfectly aligned plane-parallel faces. Externally, the situation is nearly perfect. But inside the medium, these reflectors and their alignment appear to be far from perfect, especially if the index of refraction suffers extreme gradients across the cross section of the rod. This study was therefore concerned with recognizing the optical situation inside the medium and learning how it is related to some of the external parameters influencing maser action in ruby. To this end, it was hoped that elastic deformation could provide a means systematically to vary the material's optical properties.

Consider, for example, an end-loaded cantilevered ruby rod. If we consider pure bending, which is a close approximation for the dimensions involved, the loaded end suffers a deflection of θ radians given by the expression[6]

$$\theta = \frac{1}{2}\frac{Wl^2}{EI}, \tag{1}$$

where

W = weight of load
l = length of rod
I = moment of inertia about a cross section
E = Young's modulus for the material.

If we put in values appropriate to a ruby rod[7] of circular cross section and dimensions of 2.5 mm diameter, 35 mm length, and with a load of 100 gm, the deflection will be 0.85×10^{-3} radians, or approximately 3 minutes. If the faces of the rod were originally parallel, this angle is the extent to which they are now inclined.

Below the neutral axis the rod is in longitudinal tension; above it, it is in compression (if the load bears upward). The transverse cross section, however, finds itself stressed in just the opposite fashion. Below the neutral axis the cross section is in compression; above it, it is in tension. This fact is governed in an isotropic medium by the expression[8]

$$\epsilon_y = \epsilon_z = -\nu\frac{\sigma_x}{E}, \tag{2}$$

where

E = Young's modulus
ν = Poisson's ratio
σ_x = axial stress
ϵ_y, ϵ_z = corresponding transverse strains.

The indices of refraction are closely related to stress and strain, and if n_y and n_z are the indices for each polarization of light propagated in the x direction, they will be governed by equations of the form[9]

$$\begin{aligned} n_y - n &= c_1\sigma_z + c_2(\sigma_y + \sigma_x), \\ n_z - n &= c_1\sigma_y + c_2(\sigma_z + \sigma_x), \end{aligned} \tag{3}$$

where

n = (isotropic) index for zero stress
σ_y, σ_z = stresses in the y–z plane
c_1, c_2 = stress-optical coefficients.

A wave front propagating down the axis of the rod can, therefore, be tilted or otherwise altered by inducing appropriate stresses that differentially retard parts of the wave front. This is a great oversimplification, of course, since ruby is very anisotropic. For completeness the stress-optical relations must be expressed in tensor form.[10] Nevertheless, we are interested in the gross effect, although in future experiments the lack of data on stress-optical coefficients of ruby must be

remedied. However, an order-of-magnitude estimate of the optical effect in the original example of a flexed ruby rod can be made by assuming that the parallelism of the reflecting ends as seen from within the medium is altered to a similar degree as seen from without.

Bulk ruby contains systematic and random gradients in the index of refraction. We are led to expect, therefore, that the stress-optic effect of elastic deformation can be made to compensate the most uniform volume, and effectively realign the reflecting faces to optimum resonance from the point of view of radiation inside the medium.

The Apparatus

In the manner described by Miles[4] and Edgerton[5] excitation was provided by a closely nesting arrangement of four FX-100 xenon flashlamps. They surrounded a ruby rod, as shown in Fig. 1, which was cantilevered by means of a collet. Stressing was accomplished by variably loading the free end of the rod with weights that connected to it through the harness, string, and pulley arrangement shown in Fig. 1. In this way, the flashlamps suffered no interference from the stressing assembly. The free end, therefore, was loaded vertically upward. Optical maser action was observed from the supported end of the ruby rod through the collet. The collet was indexed and free to rotate so that the load could be applied over 360° about the axis of the rod.

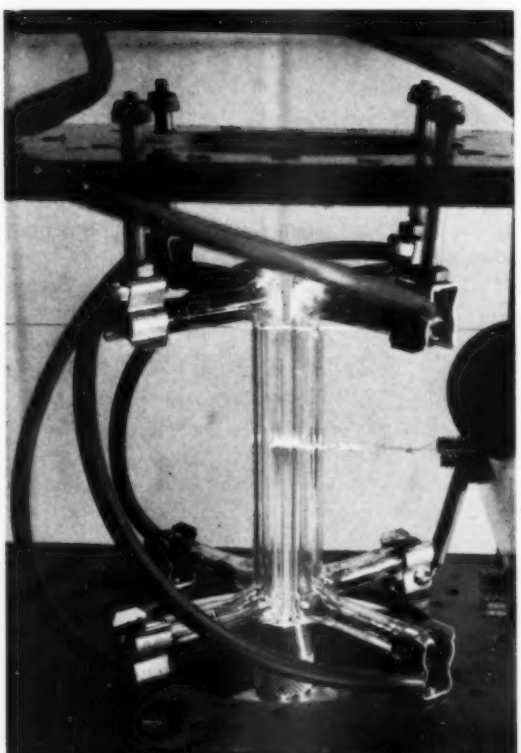


Fig. 1. Close-up of ruby optical maser assembly and flashlamps.

A strip of aluminum foil ordinarily surrounded the flashlamps at the ruby to act as a reflector and trigger electrode, but it has been removed here for clarity in this photograph.

Figure 2 shows the over-all arrangement by means of which simultaneous time and spatial developments were observed and photographed. The emergent light from the maser encounters filters, a beam splitter, and a single-lens reflex camera focused on infinity for far-field exposures, or on the emitting face of the rod for near-field exposures. A small fraction of the light is reflected from the beam splitter into a photoelectric detector.

The detector consisted of a 925 phototube, and by virtue of short leads it could easily resolve light pulses of less than a microsecond duration.

Except for brief reference to maser rods of larger diameter, the results given here refer to several different 2.5-mm rods cut from a single slow-grown, well-annealed ruby boule. These rods were blocked together for lapping, and differ only because of local variations in the index of refraction from one part of the original boule to the next.

Multiple dielectric reflector coatings were used for reasons of durability and suitability for photography. However, sufficient experiments were also conducted with silver coatings to show that the results would be substantially independent of the kind of coating used.

Results

Photographs of three different ruby optical masers for different conditions of input energy, amounts of loading, and directions of stress are presented in Figs. 3–23. The rods were 38 mm long and 2.5 mm in diameter, and were taken from a single ruby boule. The reflecting faces of each rod were optically polished to flatness better than $1/4$ wave of sodium light and parallelism within a few seconds of arc. Each rod had been clamped around its circumference; this left a cantilevered length of 35 mm extending from the collet and loaded at its extreme end in the manner described above.

The first set of photographs contained in Figs. 3–8 were taken with one of the rods, labeled No. 1, set up in the way described. Its orientation was such that with a unique amount of stress the rod required the least excitation energy for the onset of maser action. In this case the *c* axis was horizontal. Figures 3(a), 4(a), 5(a), 7(a), and 8(a) are near-field photographs for stressing loads increasing from 0 to 150 gm, while Figs. 3(b), 4(b), 5(b), 6, 7(b), and 8(b) are far-field photographs of the corresponding near-field patterns. Table I summarizes the conditions for these figures.

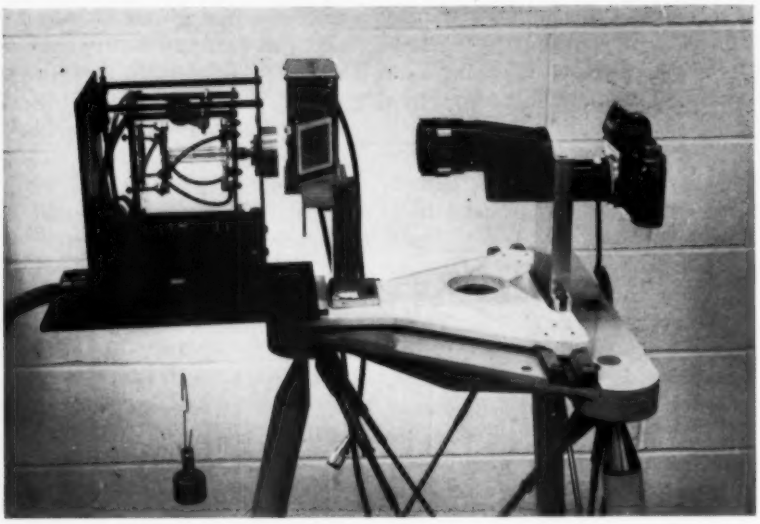


Fig. 2. Over-all view of apparatus.

The original photographs were on 35-mm film. The far-field photographs were taken by means of a 650-mm focal length lens, and, including enlargement, this corresponds to an equivalent focal length of 90 in. (2.28 m) that gives rise to the final pattern diameters in the original prints for these figures.

The near-field photographs show the emitting face of the ruby optical maser greatly enlarged. Thus, minute imperfections in its surface area and in the reflective coatings are greatly exaggerated. In particular, a narrow white streak that appears is a scratch in the coatings which is of no particular consequence. The four collet jaws appear in blackout of focus, while direct light from the flashlamps can be seen in the background. The ruby is protected from concentrated stresses resulting from the collet by means of a thin ring of aluminum that is clearly visible but also out of focus.

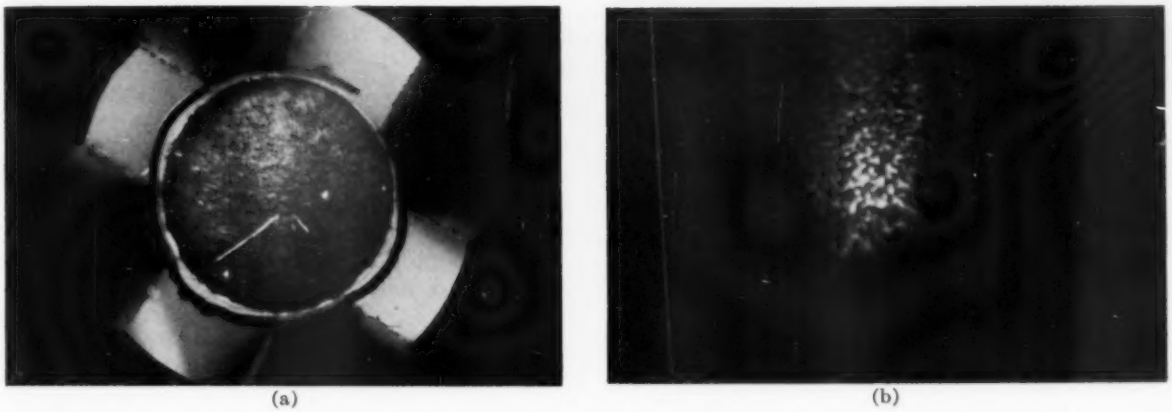
Table I. Conditions for Field Photographs of Ruby Optical Maser No. 1

Figure	Stressing load (gm)	Type of photograph	Input energy (joules)	Comments
3(a)	0	Near-field	285	Threshold
3(b)	0	Far-field	285	Threshold
4(a)	43	Near-field	250	Threshold
4(b)	43	Far-field	250	Threshold
5(a)	91	Near-field	194	Threshold
5(b)	91	Far-field	194	Threshold
6	91	Far-field	285	Above threshold
7(a)	129	Near-field	214	Threshold
7(b)	129	Far-field	214	Threshold
8(a)	150	Near-field	260	Threshold
8(b)	150	Far-field	260	Threshold

The near-field radiation patterns can be easily distinguished from surface imperfections by examining several photographs in the set. They appear as the white topography that varies in structure with the applied stress. Ideally, one would hope for a uniform intensity distribution across the face of the rod with no structure characteristic of high-order radiation modes. It can be seen in these photographs to what extent this behavior can be achieved as deformation is increased to an optimum degree and beyond. The far-field patterns give some indication of the phase relationships underlying these modes, and in some cases, which will be discussed, they show that over surface areas with diameters as large as 0.5 mm the mode is effectively first order.

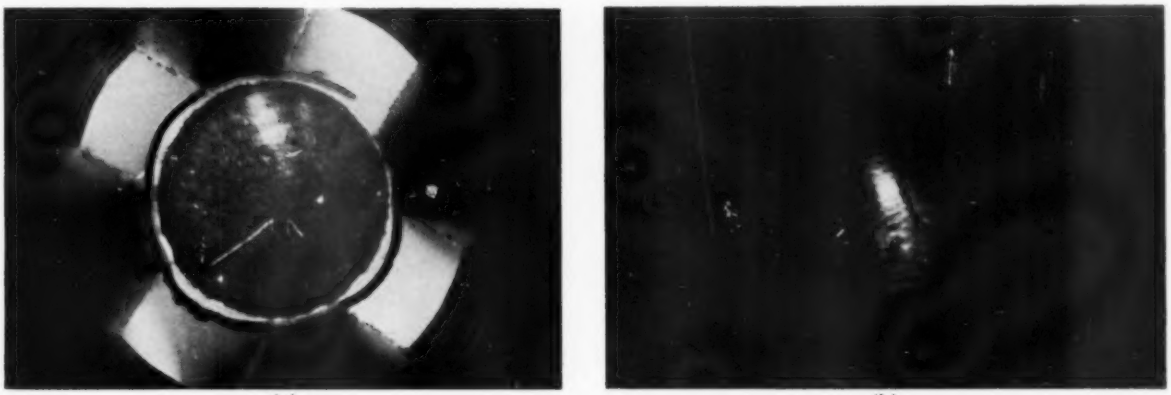
Figure 6 is a particularly interesting case because it shows in great detail the characteristic structure at infinity of radiation from a Fabry-Perot resonator. It also shows to what extent the intensity of radiation from a ruby optical maser can be increased for the same energy input when the resonator is deformed in the way described.

It is important to note that all of the photographs taken at threshold were essentially invariant for time developments of a single pulse or a small group of pulses. Within the sensitivity of the equipment, it could not be determined that the threshold photographs could be influenced except in intensity and in minor details as the input energy was varied just above threshold. The photographs taken above threshold were, of course, considerably more complicated and their time developments were exceedingly complex. Yet the field patterns always consisted essentially of threshold behavior that had become more or less obscured by a background of radiation from high-



(a) (b)

Fig. 3. (a) Near-field pattern of ruby optical maser No. 1 for zero load, 285 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 4. (a) Near-field pattern of ruby optical maser No. 1 for 43-gm load, 250 joules input. (b) Far-field pattern of (a).

(a) (b)

Fig. 5. (a) Near-field pattern of ruby optical maser No. 1 for 91-gm load (the condition for lowest threshold), 194 joules input. (b) Far-field pattern of (a).

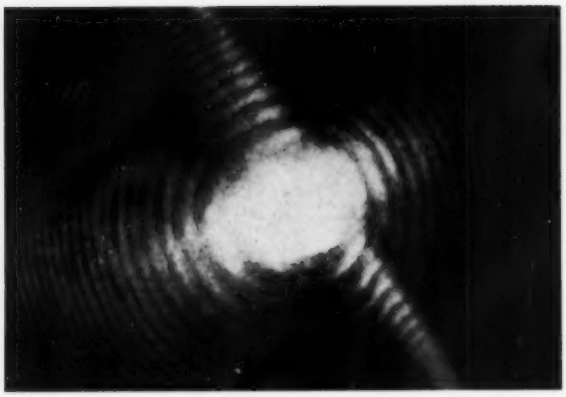


Fig. 6. Far-field pattern of Fig. 5 (b) with 285 joules input.

order modes.

The next set of photographs, Figs. 9–15, were taken with maser No. 2 under a similar set of conditions. Orientation had again been chosen for maximum effect, except for Fig. 15(a) and 15(b) in which the rod has been rotated 90° to show the negative effect for other than a preferred direction. Table II summarizes the conditions for these photographs.

In the near-field photographs of this set pinholes and other minor imperfections are again discernible, but once they are recognized as such they are clearly innocuous.

Figures 10–13 are of particular note, for here the rods have been constrained to emit in relatively simple modes in contrast to the unstressed condition. In addition the conditions of Figs. 11 and 12 demonstrate that the threshold has been reduced from 306 joules to 196 joules.

The final set of photographs in Figs. 16–23 was obtained with maser No. 3 in the same way as the others. This rod was of special interest because in the unstressed condition it showed a substantially lower threshold. Stressing, however, provided a clue to this behavior, and under the right conditions, as seen in this set, rod No. 3 was constructed to optimum behavior not essentially different from that in the first two cases. Table III gives the conditions, and once again a single pair of photographs [Fig. 23(a) and 23(b)] demonstrates the interesting but negative effect of stressing in a nonpreferred direction.

All of the preceding results are consistent with many additional experiments on various ruby rods of larger diameter but similar length. Without exception, however, the larger rods had higher threshold.

It is of particular interest that the thresholds quoted above could be greatly reduced with a different flash-lamp arrangement. For example, ruby optical maser No. 3 could be operated at a threshold below 85 joules at room temperature in an elliptic reflector arrangement similar to the one reported by Çiftan and others.[3] This was for the unstressed rod, and no doubt this figure could easily be lowered with the technique of elastic deformation.

III. Discussion

The preceding photographs and accompanying data make it immediately apparent that elastic deformation can have a profound effect on the characteristics of ruby optical masers and, therefore, on optical masers of other crystalline media. The nature of this effect and the conclusions that can be derived from these results require discussion at some length.

Threshold Conditions

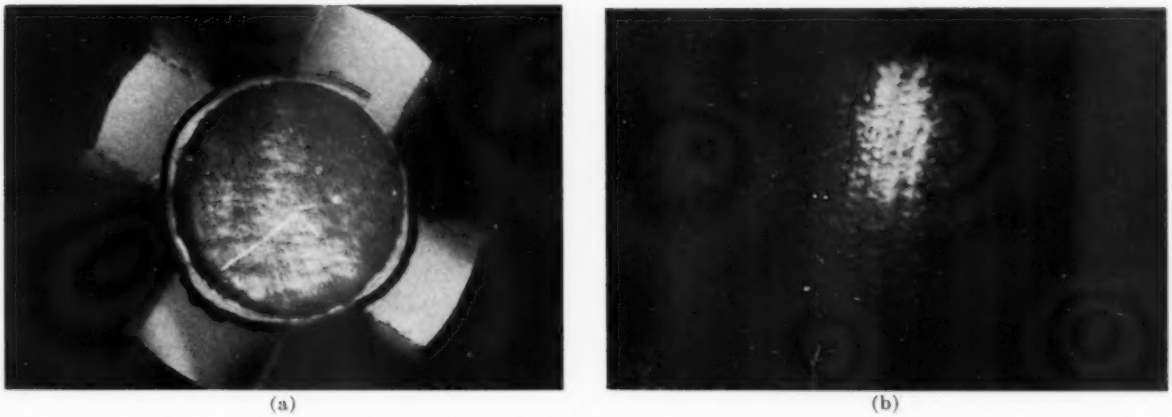
Near- and far-field radiation patterns were obtained at threshold conditions for which time development had been simultaneously monitored and observed as a single microsecond pulse, or several pulses in an interval of a few microseconds. As long as the input-energy remained just above threshold, the field pat-

Table II. Conditions for Field Photographs of Ruby Optical Maser No. 2

Figure	Stressing load (gm)	Type of photograph	Input energy (joules)	Location of c axis	Comments
9(a)	0	Near-field	306	Vertical	Threshold
9(b)	0	Far-field	306	Vertical	Threshold
10(a)	91	Near-field	242	Vertical	Threshold
10(b)	91	Far-field	242	Vertical	Threshold
11(a)	150	Near-field	196	Vertical	Threshold
11(b)	150	Far-field	196	Vertical	Threshold
12(a)	188	Near-field	196	Vertical	Threshold
12(b)	188	Far-field	196	Vertical	Threshold
13(a)	188	Near-field	228	Vertical	Above threshold
13(b)	188	Far-field	228	Vertical	Above threshold
14(a)	300	Near-field	250	Vertical	Threshold
14(b)	300	Far-field	250	Vertical	Threshold
15(a)	91	Near-field	314	Horizontal	Rotated 90°, threshold
15(b)	91	Far-field	314	Horizontal	Rotated 90°, threshold

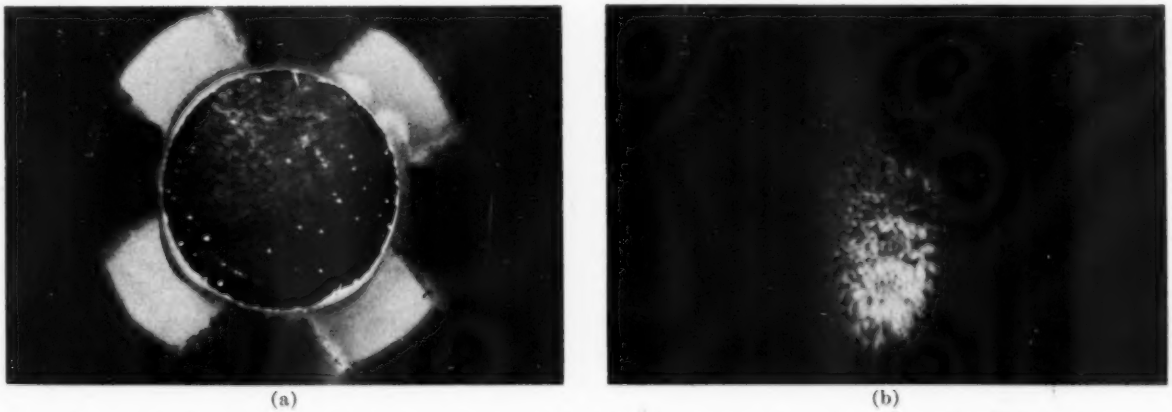
(a) (b)

Fig. 7. (a) Near-field pattern of ruby optical maser No. 1 for 129-gm load, 214 joules input. (b) Far-field pattern of (a).



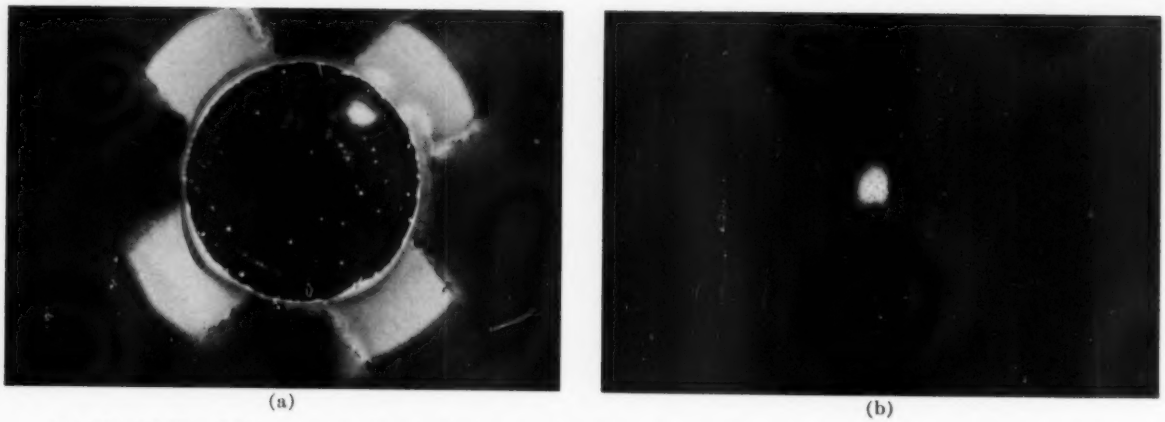
(a) (b)

Fig. 8. (a) Near-field pattern of ruby optical maser No. 1 for 150-gm load, 260 joules input. (b) Far-field pattern of (a).



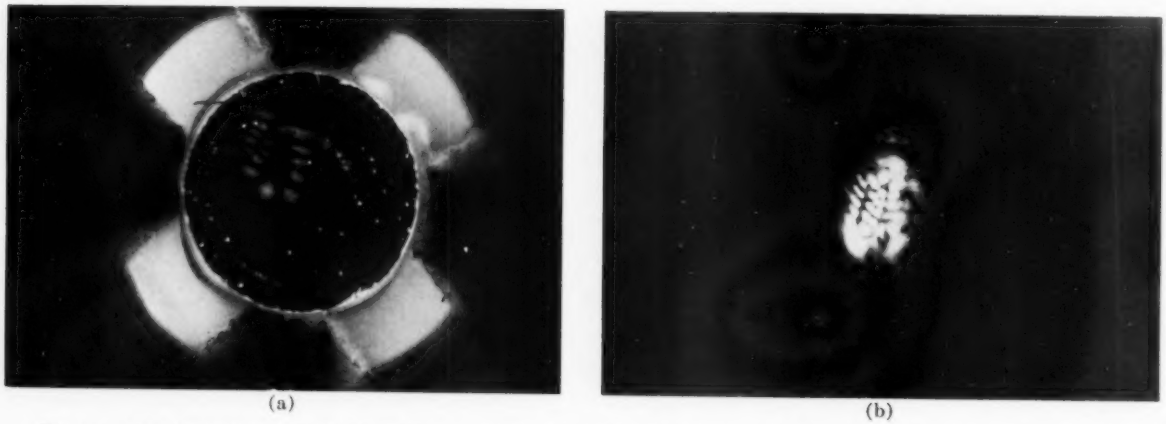
(a) (b)

Fig. 9. (a) Near-field pattern of ruby optical maser No. 2 for zero load, 306 joules input. (b) Far-field pattern of (a).



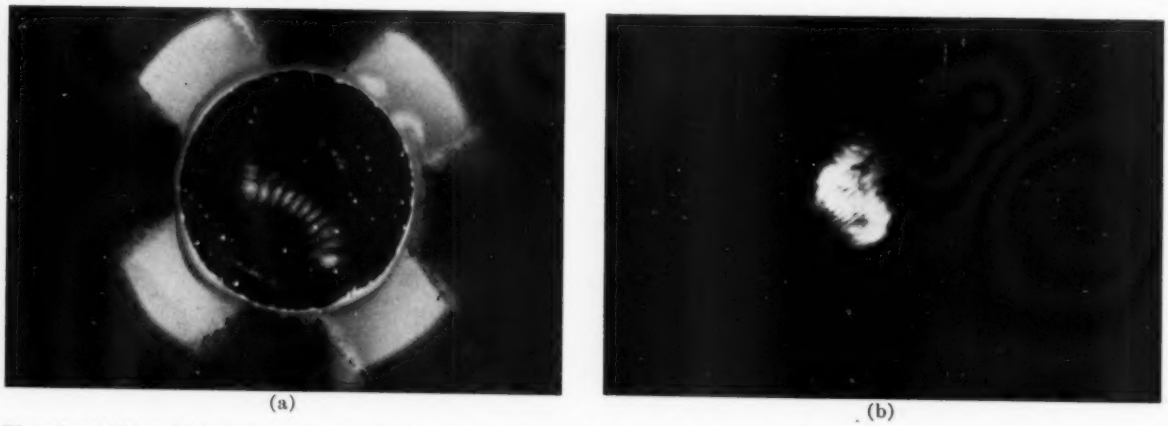
(a) (b)

Fig. 10. (a) Near-field pattern of ruby optical maser No. 2 for 91-gm load, 242 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 11. (a) Near-field pattern of ruby optical maser No. 2 for 150-gm load, 196 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 12. (a) Near-field pattern of ruby optical maser No. 2 for 188-gm load (the condition for lowest threshold), 196 joules input. (b) Far-field pattern of (a).

terns were insensitive to variations in the time development. Figure 16(b), for example, is the pattern of a single microsecond pulse of maser radiation. This is clearly not the pattern from a simple mode, yet all of the radiation took place in a microsecond, and one is led to the conclusion that when the system broke into oscillation, it did so in a single complex mode (or a small number of modes) with the topography shown in Fig. 16(a). This conclusion is supported by the corresponding near-field pattern, Fig. 16(a), and in fact by all of the field-pattern pairs. Had the radiation been emitted at random from a collection of apertures with the same general topography, then, from the point of view of Fraunhofer diffraction, each aperture would have contributed intensity but not phase to the far-field. As a result, the far-field would have appeared to be a more or less continuous blur rather than the structured pattern that had been photographed.

The results of Statz and others,[11] although not stated in such terms, lend support to this conclusion. They actually sampled radiation from different areas in the near-field and observed correlation in the time developments.

Field-Pattern Pairs

Photographs of field-pattern pairs have been presented for each of three ruby optical masers for a range of conditions. In each case, reduction in complexity of the field patterns by as much as orders of magnitude can be noted when the maser rods are put under stress to the optimum extent.

Let us consider the threshold field patterns of the unstressed masers (Figs. 3, 9, and 16 for ruby optical masers Nos. 1, 2, and 3, respectively). Each far-field pattern strikingly resembles the Fraunhofer diffraction pattern from an irregular distribution of apertures in a plane screen.* Indeed, this is the character of the corresponding near-field patterns. The essential difference, however, is that the maser apertures are really crests of a complex wave front, and not irregular apertures before a plane wave front. The result is the same, nevertheless. Each crest contributes to the far-field pattern according to its phase, and thus the characteristic patterns given in the figures arise in the far field.

Now let us consider the threshold field patterns of the stressed masers (Figs. 5, 10, 11, and 20 especially) in which radiation modes, evidently, are greatly reduced in complexity.

Some interesting relations appear between each field-pattern pair if we make the simplifying assumption that the emergent radiation is approximately equivalent to a plane wave diffracted by a screen containing apertures that give roughly the appearance of each near-field pattern. In the simplest case, Fraunhofer diffraction is expressed by the equation

$$\alpha = \frac{n\lambda}{d}, \tag{4}$$

where

α = beam divergence
λ = wavelength of radiation (6943 Å)
d = size of aperture
n = index of refraction of ruby (1.74).

At the focal plane of a lens this beam produces a diffraction spot size

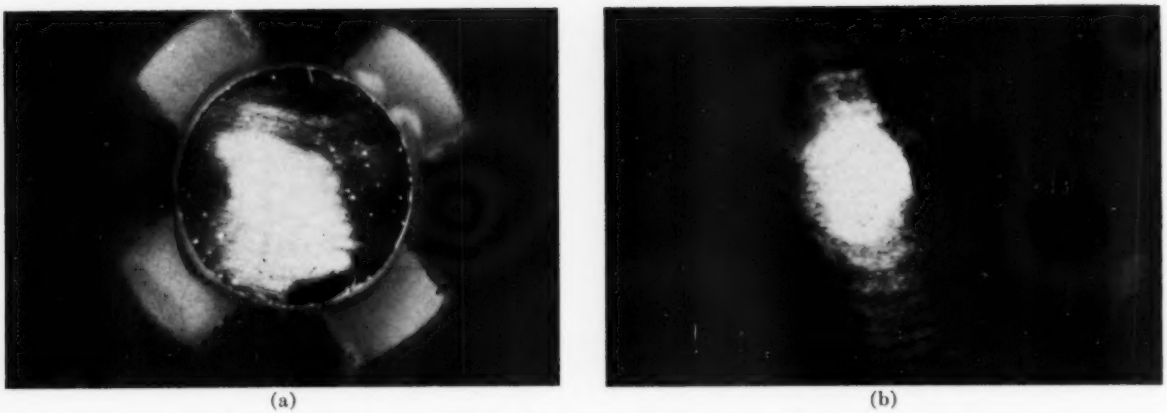
$$D = \frac{n\lambda f}{d}, \tag{5}$$

where f is the focal length of the lens.

* See Figs. 8–15 of Born and Wolf.[10]

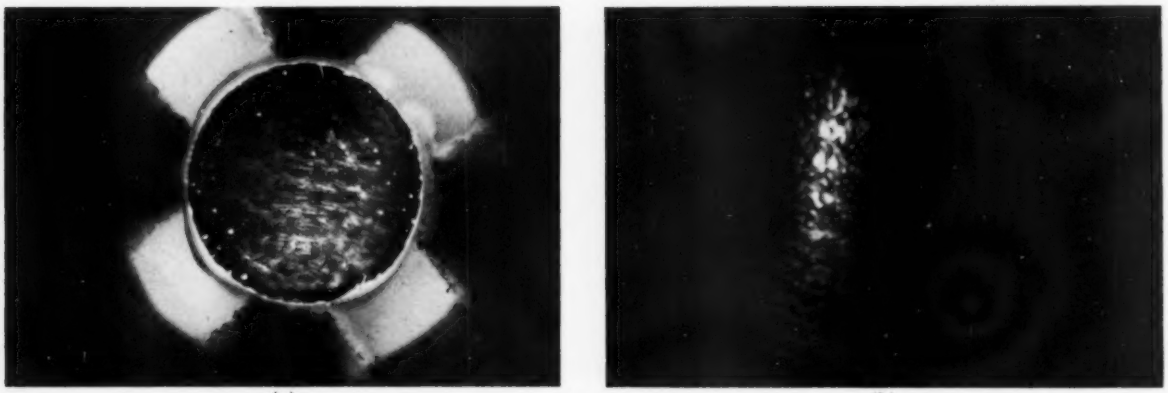
Table III. Conditions for Field Photographs of Ruby Optical Maser No. 3

Figure	Stressing load (gm)	Type of photograph	Input energy (joules)	Location of c axis	Comments
16(a)	0	Near-field	207	Vertical	Threshold
16(b)	0	Far-field	207	Vertical	Threshold
17(a)	0	Near-field	250	Vertical	Above threshold
17(b)	0	Far-field	250	Vertical	Above threshold
18(a)	22	Near-field	185	Vertical	Threshold
18(b)	22	Far-field	185	Vertical	Threshold
19(a)	32	Near-field	185	Vertical	Threshold
19(b)	32	Far-field	185	Vertical	Threshold
20(a)	43	Near-field	185	Vertical	Threshold
20(b)	43	Far-field	185	Vertical	Threshold
21(a)	43	Near-field	250	Vertical	Above threshold
21(b)	43	Far-field	250	Vertical	Above threshold
22(a)	150	Near-field	285	Vertical	Threshold
22(b)	150	Far-field	285	Vertical	Threshold
23(a)	150	Near-field	285	Horizontal	Rotated 90°, threshold
23(b)	150	Far-field	285	Horizontal	Rotated 90°, threshold



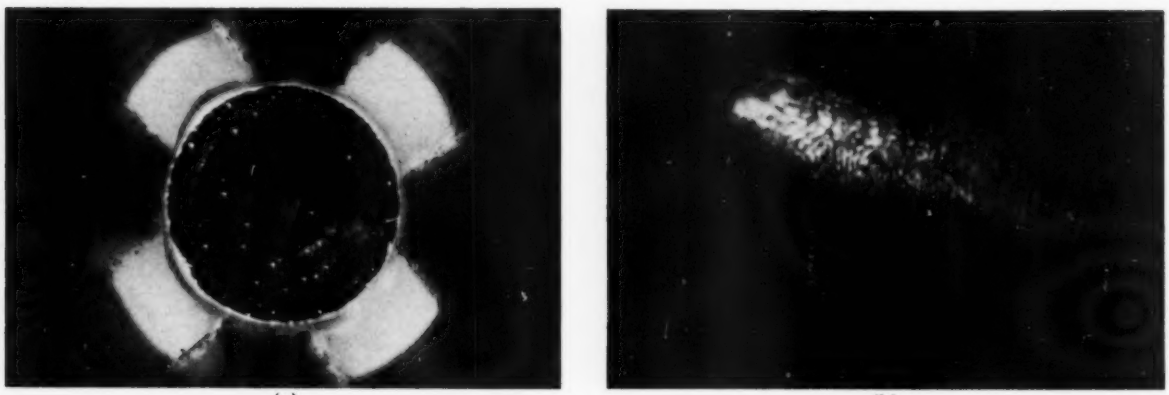
(a) (b)

Fig. 13. (a) Near-field pattern of Fig. 12(a) with 228 joules input. (b) Far-field pattern of (a).



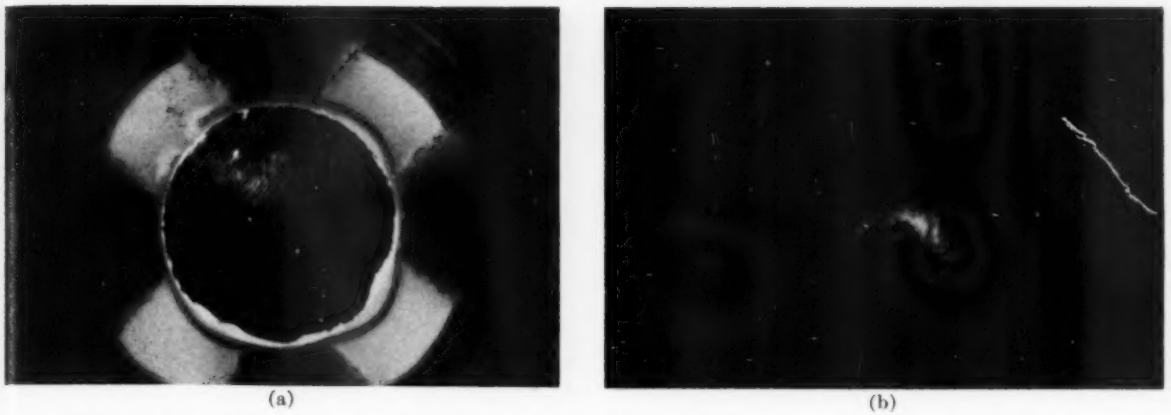
(a) (b)

Fig. 14. (a) Near-field pattern of ruby optical maser No. 2 for 300-gm load, 250 joules input. (b) Far-field pattern of (a).



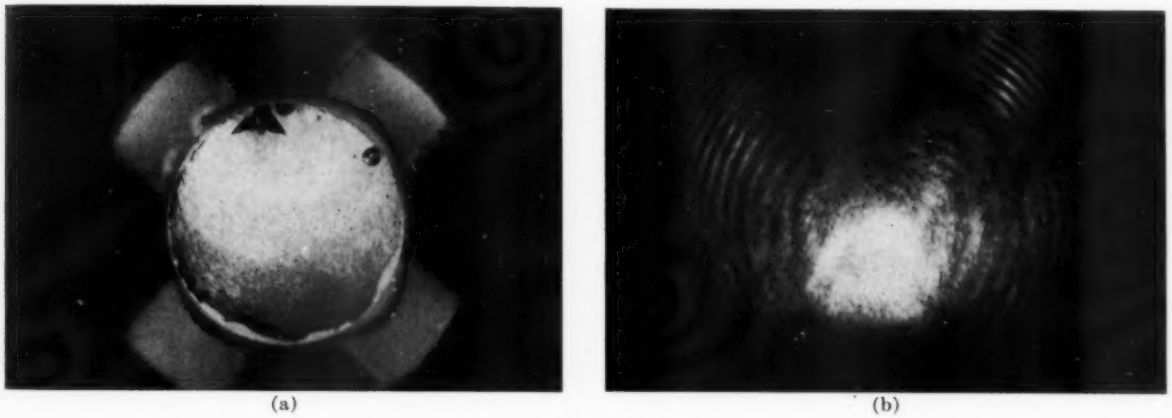
(a) (b)

Fig. 15. (a) Near-field pattern of ruby optical maser No. 2 rotated 90°, for 91-gm load, 314 joules input. (b) Far-field pattern of (a).



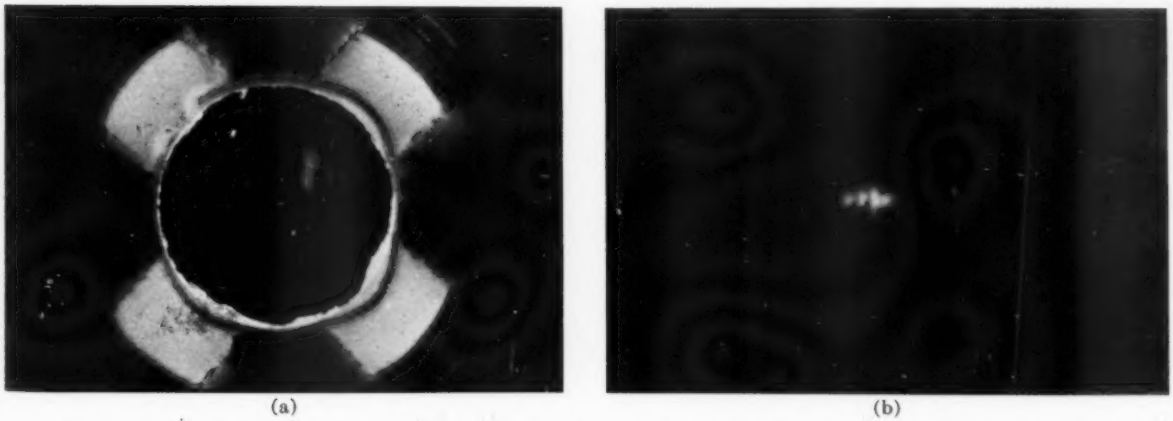
(a) (b)

Fig. 16. (a) Near-field pattern of ruby optical maser No. 3 for zero load, 207 joules input. (b) Far-field pattern of (a).



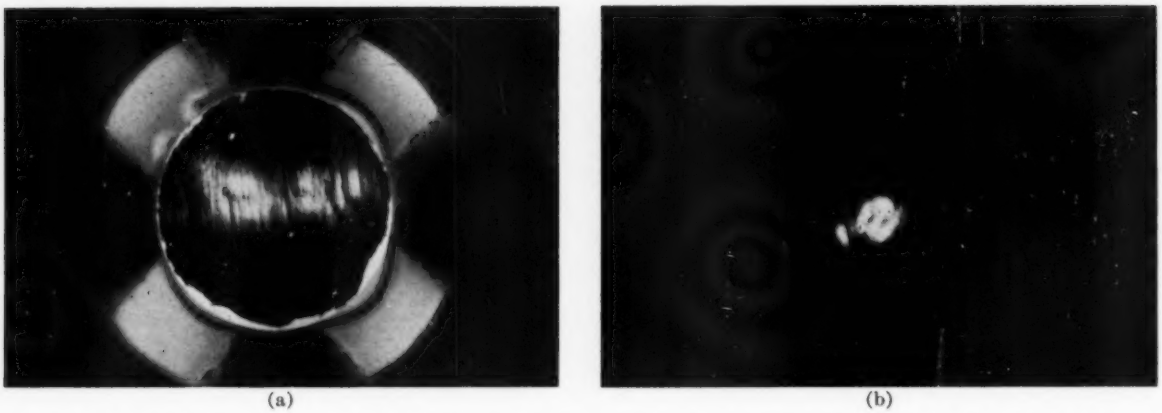
(a) (b)

Fig. 17. (a) Near-field pattern of Fig. 16 (a) with 250 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 18. (a) Near-field pattern of ruby optical maser No. 3 for 22-gm load, 185 joules input. (b) Far-field pattern of (a).



(a) (b)

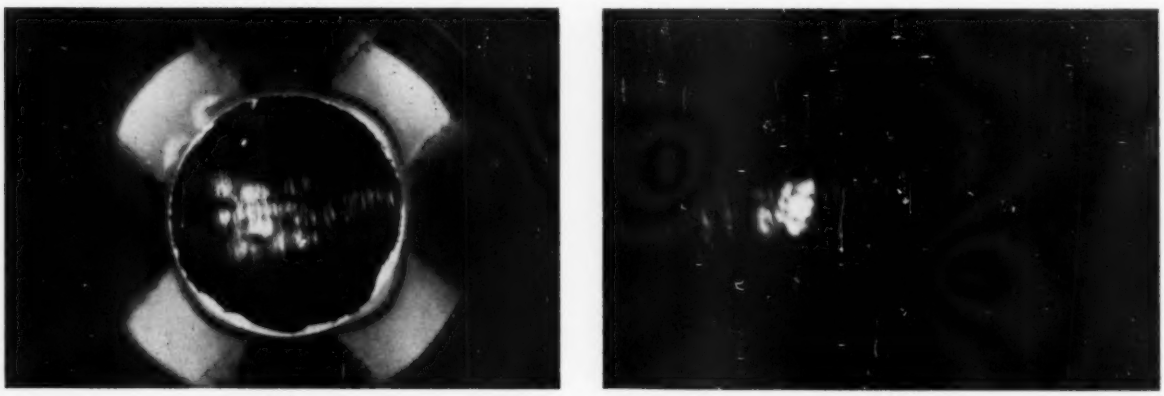
Fig. 19. (a) Near-field pattern of ruby optical maser No. 3 for 32-gm load, 185 joules input. (b) Far-field pattern of (a).

Consider, for example, the brightly radiating spot shown in Fig. 10(a). The actual diameter of this spot is approximately 0.25 mm. An aperture of this size would diffract a plane wave according to (4), and should produce in far-field a 10-mm diameter patch according to (5). Nearly as predicted, the patch in Fig. 10(b) is actually 8 mm in diameter.

Figures 11 and 12 are particularly interesting examples of field-pattern pairs. Here the near-field patterns must indeed be due to a rippled but coherent wave front in order to produce such finely resolved far-field patterns. The size of the blurred structure in far-field correlates well with the size of the fine structure in near field. Conversely, the gross structure in near field correlates well with the fine structure in far field.

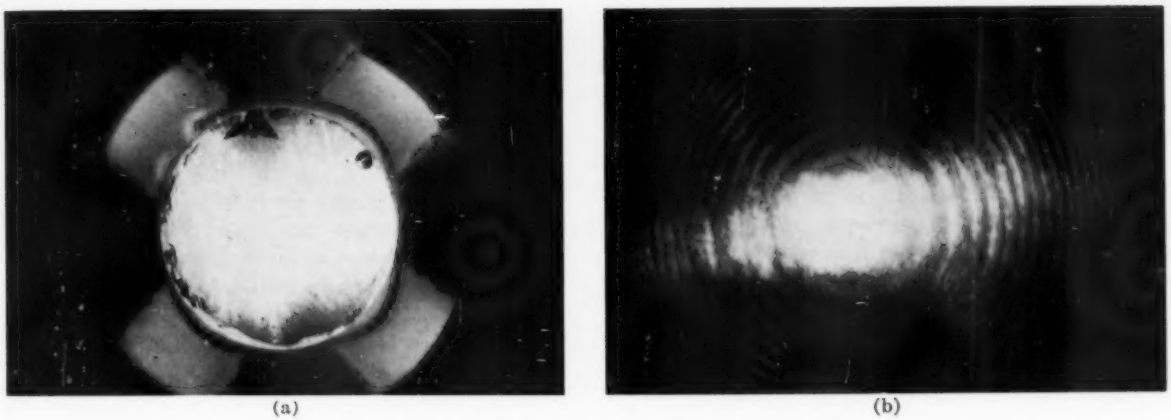
Note that in cases such as those shown in Figs. 11(a) and 12(a) the wave fronts extend over much of the 2.5-mm diameter of the ruby optical maser, yet a single crest of the near-field pattern is never much larger than the bright patches in Figs. 10(a) and 5(a). These patches are from 0.25 to 0.5 mm in diameter, and this seems to be the maximum size of the nearly plane wave front that the medium can sustain. The far-field patterns agree with this conclusion to the extent that the least beam divergence that could be obtained was approximately 8 minutes of arc or, from Eq. (4), the divergence from an aperture of approximately 0.5 mm.

Note, however, that this beam divergence taken from Fig. 5(b) represents a five times, or more, improvement over the unstressed case of Fig. 3(b). Similar improvements are evident in Figs. 9(b) and 12(b), and in Figs. 16(b) and 20(b). This is obviously consistent with constraining the radiation modes to those of low order.



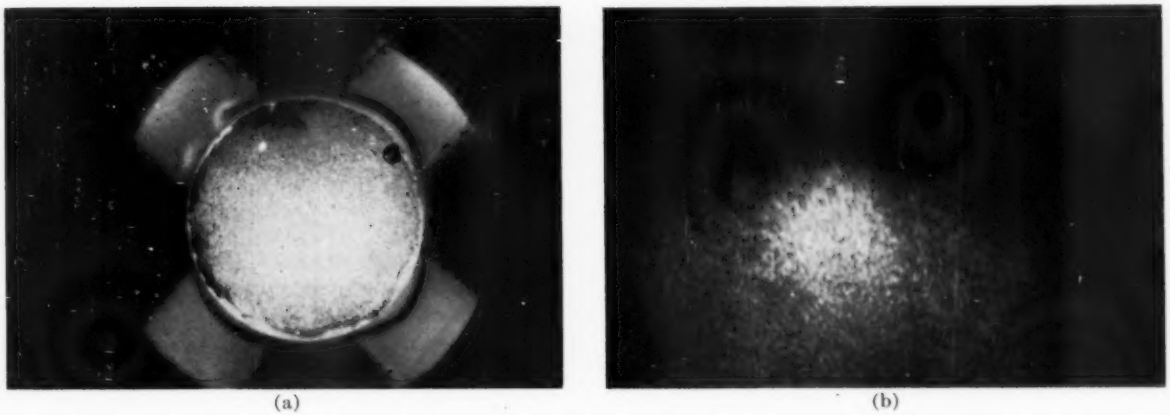
(a) (b)

Fig. 20. (a) Near-field pattern of ruby optical maser No. 3 for 43-gm load (the condition for lowest threshold), 185 joules input. (b) Far-field pattern of (a).



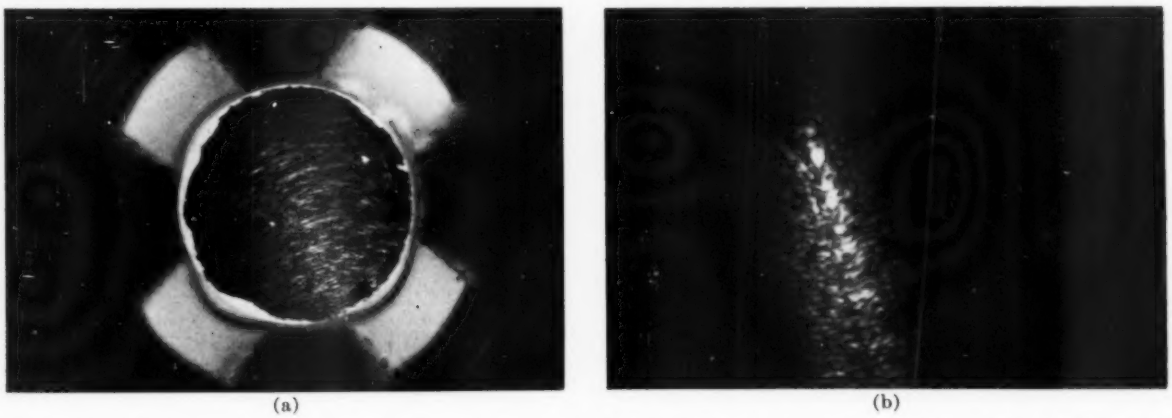
(a) (b)

Fig 21 (a) Near-field pattern of Fig. 20 (a) with 250 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 22. (a) Near-field pattern of ruby optical maser No. 3 for 150-gm load, 285 joules input. (b) Far-field pattern of (a).



(a) (b)

Fig. 23. (a) Near-field pattern of ruby optical maser No. 3 rotated 90°, for 150-gm load, 285 joules input. (b) Far-field pattern of (a).

Fabry-Perot Rings

When more energy is made available, and when the radiation mode structure is not too complicated, sufficient detail can be resolved at far-field to illustrate the Fabry-Perot resonator nature of ruby optical masers[12] (with plane-parallel faces). This is illustrated in Figs. 6, 12(b), 17(b), and 21(b). In particular, Figs. 17(b) and 21(b) (for ruby optical maser No. 3) show to what extent the ring system can be cleaned up when less complicated modes are constrained to radiate. In contrast, ruby optical maser No. 1 and ruby optical maser No. 2 hardly showed vestiges of a ring system until they were optimally deformed.

Measurement of the ring diameters and a simple calculation show that the patterns indeed obey the equation[10]

$$D_p^2 = \frac{4n'\lambda_0 f^2}{n^2 h}(p-1), \tag{6}$$

where

D_p = diameter of pth ring
n' = index of refraction of ruby
h = length of maser rod
λ_0 = free-space wavelength of radiation
n = index of refraction of the air outside the rod
f = focal length of camera lens.

Radiation-Mode Diffraction Loss

In ruby optical masers, oscillation begins in the highest Q mode of a given system. If the system happens to appear optically as an inhomogeneous medium between imperfectly aligned reflectors, then the highest Q mode will correspond to the one with the least number of phase reversals over the diameter of the medium coupled to the radiation field. We have seen how the number of phase reversals can effectively be reduced to unity as the reflectors are brought into alignment, but in the case under consideration the maximum diameter of the medium working into that mode is limited by the quality of the medium to approximately 0.5 mm.

Fox and Li[13] have calculated the diffraction loss to be expected in such a situation, and for the fundamental mode the power loss per reflection amounts to approximately 15%. Higher-order modes lead to greater power loss per reflection. Therefore, it is not surprising that the input-energy thresholds were reduced in every case when the radiation modes were simplified to the extent shown in the figures.

The controlling parameter for diffraction loss is given by the ratio $b\lambda/a^2$, where $2a$ is the active diameter of the medium, b is the distance between the reflectors, and λ is the wavelength of the radiation in the medium.

Physical Considerations

With power loss caused by diffraction as high as 15% per reflection, it is easy to understand why optical masers show little sensitivity to the transmittance of their reflective coatings, whether they be metallic or multiple dielectric. Evidently, only when power loss resulting from unusually low reflectance overrides that caused by diffraction can maser characteristics be greatly influenced by coating considerations.

Manufacturers of ruby rods for optical maser purposes strive, at the present time, for $^1/_{10}$ wave flatness over 6-mm faces, and 5-sec. wedge tolerance over 5-cm lengths. In the light of our results, it seems hardly necessary to ask for better than $^1/_{10}$ wavelength over 0.5 mm (approximately 1 wavelength over 6 mm) and a wedge better than 1 minute of arc. Otherwise, the optical surfaces would be far better than the ruby itself. On the other hand, if diminished lengths and diameters were to be considered, optical tolerances would be more stringent.

It can be shown that for maser action, input-energy requirements are proportional to the cross-section area of the medium.[14] For efficiency reasons alone, therefore, it is inadvisable to work with diameters greater than those which the medium can sustain in a low-order radiation mode.

Future work along the lines presented here should be carried out on ruby optical masers with diameters smaller than 1 mm. Their lengths should be selected on the basis of tolerable diffraction loss per reflection, provided that this is consistent with the gain per unit length of the medium. The same experiments should also be performed at low temperatures for which lower thresholds can be expected.

Identical considerations apply to 4-level optical masers. In fact, similar results could reduce threshold to an amount which allows c.w. operation of present solid-state optical masers. Perhaps when this is done it will appear less remarkable that, for all its inhomogeneities and tremendous radiation mode densities, ruby can be induced to radiate into low-order modes extending thousands of wavelengths across the medium.

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photo D. J. Troy

Attendees at the London July 1961 ICO Conference on Optical Instrumentation leaving the Imperial College Physics Building: O. S. Heavens, *Royal Holloway College*, P. R. Wakeling, *OSA*, J. M. Burch, *National Physical Laboratory*, and R. G. Giovanelli, *CSIRO, Australia.*

R. Kingslake and R. M. Blakney from Rochester talking with a friend in the new Physics Department at Imperial College, London, during the July 1961 ICO sessions.

Books

continued from page 342

given by the Stefan-Boltzmann law). This fractional function $B(v)$ is a dimensionless number between 0 and 1, where $v = \lambda T/c_2$. Thus these tables are independent of the value of c_2. The chief advantage of this small book over the larger tables of Pivavonsky and Nagel is that the authors have also tabulated $B'(v)$ and $B''(v)$, the first and second derivatives of $B(v)$ with respect to v, and also $B^*(v)$, where $B^*(v) = B(v) + (1/4)\,v\,B'(v)$, as well as its derivative $B^{*\prime}(v)$. These auxiliary functions are useful in certain radiation transfer calculations. There is a good discussion of how to interpolate in the tables and some examples are worked out for practical applications. The text is in English and German.

J. N. HOWARD

The Physical Basis of Polarized Emission. By P. P. FEOFILOV. Consultants Bureau, New York, N. Y., 1961. 274 pp. $12.50.

This brief, crudely manufactured book is aimed at physical chemists, not optical men. The title of the 1957 Russian version ("Polarized Luminescence of Atoms, Molecules, and Crystals") indicates the true concern of the book: mechanisms of luminescence. Elementary quantum mechanical principles of energy levels and transitions are touched upon, and some experimental results on degree of polarization of light emitted by various fluors and phosphors are presented. The typography is poor, the bibliography is disorganized, and there is no index.

W. A. SHURCLIFF

IUPAC Tables of Wavenumbers for the Calibration of Infrared Spectrometers. Butterworths, Washington, D.C., 1961. 172 pp., $6.00.

One of the most urgent requirements of infrared spectroscopists in general has been a comprehensive set of authoritative wavenumber standards covering a wide spectral range. This volume, compiled by the Commission on Molecular Structure and Spectroscopy, adequately supplies several such sets and, in attempting to serve as wide a range of interests as possible, caters equally well to those interested in high-resolution vibration-rotation spectra and to those who work in the solid and liquid phases, where the resolution requirements are usually much less. The book contains some 93 spectra in all, each covering about 150 cm^{-1} and each having an accompanying table identifying those lines which have been specifically selected on the basis of suitability as accurate wave-number standards.

The book is divided into two sections, the first part dealing with the calibration of grating spectrometers, with resolution between 0.1 and 1 cm^{-1}, and covering the range 4300 to 600 cm^{-1}. The calibrants are readily available commercial gases, and the absolute accuracy of the standards is quoted mostly as 0.02 cm^{-1}. The molecular data are quoted in wave numbers in vacuo, and a complete conversion table for wavelengths in air to wave numbers in vacuo, together with a table of standard infrared wavelengths and wave numbers of atomic emission lines for the range 10,000 to 4000 cm^{-1}, are included. Various procedures for calibrating the spectrometers are concisely discussed.

Part 2 deals with the calibration of prism and small grating spectrometers having resolution between 0.5 and 10 cm^{-1} and the data cover the range 3950–650 cm^{-1}. In order to provide suitable standards, the spectra in this section have been recorded on instruments whose resolution lie in the range 0.5–10 cm^{-1}, and so naturally the absolute accuracy of these standards is much less than those in Part 1. Many of the same gases used in the first section have been used as calibrants here, as well as several liquid and solid phase substances. Resolution tests are included throughout the range, which should prove particularly useful.

The reviewer strongly recommends this volume as a worthy and necessary addition to every spectroscopic laboratory.

GRAHAM R. HUNT

Information for Contributors

Scope: Papers are welcomed in the broad areas of applied optics, in disciplines related to optics and employing optical techniques. Papers should be sent to *The Editor, APPLIED OPTICS, 1155 Sixteenth St., N.W., Washington 6, D.C.* Manuscripts may be submitted in English, French, German, or Russian, and the presentation should be as succinct as comprehension will permit. In general, the metric system of units is preferred. One original and one carbon of the manuscript, with two sets of all illustrations, must be sent. Manuscripts should be typed double or triple spaced on one side of 22 × 28 cm (8½ × 11 in.) paper, leaving a 3.8 cm (1½ in.) margin all round.

An **abstract,** adequate as an index and summary, of not more than 100 words should appear at the beginning of the paper after the *title, author's name, affiliation, and address.* In the case of papers in a non-English language, they must be accompanied by an abstract in English as well as an abstract in the language of the paper.

Figures suitable for printer's use should be sent. Bear in mind that illustrations will normally be reduced to column width (8.4 cm—3⅜ in.—20 picas). *Halftones:* two sets of glossy prints are needed, which should be mailed flat, with any proportion or framing indicated on a working copy. *Line drawings* should be suitable for reproduction and be not larger than 22 × 28 cm (8½ × 11 in.). *Captions* should be listed on a separate sheet in addition to each caption appearing on each illustration.

Tables should be typed on separate sheets and the data therein be intelligible, by title, without reference to the text. Tables should include a minimum of vertical ruling.

References must be typed on a separate sheet, be numbered consecutively in the order of their appearance in the text, and follow this form:

1. F. C. Brown, Phys. Rev. **12,** 345 (1821).
2. J. Culpeper, *Space Optics* (Georgetown Institute of Technology Press, Washington, D.C., 1861) pp. 012, 345.

A list of abbreviations for the names of journals is published in the American Institute of Physics *Style Manual.* To make for uniformity of presentation generally, the *Style Manual,* second edition, should be used.

No **galley proofs** will be sent to authors; all proofreading will be done in the house. Therefore, an author will not see his paper from the time it is accepted and any alterations agreed between Editor and author, until it appears in print.

Letters to the Editor should follow the above suggestions, but no abstract is required.

Absorption Line Broadening in the Infrared

Darrell E. Burch, Edgar B. Singleton, and Dudley Williams

The effects of various gases on the absorption bands of nitrous oxide, carbon monoxide, methane, carbon dioxide, and water vapor have been investigated. Self-broadening effects for each of these gases have been compared with the effects of nitrogen in broadening the rotational lines within various vibration-rotation bands; the results can be expressed in terms of self-broadening coefficients. The effects produced by various foreign gases have also been compared with those of nitrogen; the results are expressed in terms of relative foreign broadening coefficients and relative collision diameters. The foreign gases studied include the nonabsorbing gases helium, oxygen, argon, hydrogen, and nitrogen and also carbon monoxide, carbon dioxide, and methane in spectral regions where there are no overlapping bands.

The fractional absorption $A'(\nu)$ of monochromatic radiation of frequency ν can be expressed in terms of Lambert's Law: $A'(\nu) = 1 - \exp[(-k(\nu)w)]$ where $k(\nu)$ is the absorption coefficient and w is the optical thickness or absorber concentration. In the case of gases $k(\nu)$ is a rapidly varying function of frequency in the infrared, and the measured fractional absorption $A(\nu)$ is strongly influenced by the spectral slit widths of the spectrographs employed. However, it has been found that the measured total absorption $\int A(\nu)d\nu$ is equal to the value of $\int A'(\nu)d\nu$, provided the limits of integration include an entire absorption band.[1] The total absorption of atmospheric absorption bands is a subject of considerable importance in studies of the earth's heat balance and in the development of infrared signaling systems. The present paper deals with the effects of various gases on the widths of the absorption lines within atmospheric bands and hence on the total absorption of atmospheric bands.

The Lorentz line shape

$$k(\nu) = \frac{S}{\pi} \frac{\alpha}{(\nu - \nu_0)^2 + \alpha^2}, \qquad (1)$$

where the line strength

$$S = \int_0^\infty k(\nu)d\nu$$

is constant, gives a fairly satisfactory approximation of absorption line shapes for the wide range of pressures in which "collision broadening" is encountered.[2] With certain approximations, it can be shown that for small values of $Sw/2\pi\alpha$ ("weak lines") the total absorption of a line is given by Sw, while for large values of $Sw/2\pi\alpha$ ("strong lines") the total absorption is given by $2\sqrt{Sa w}$.[3] Experimental results for limiting cases are in agreement with these predictions; total absorption for entire bands can in certain cases be correlated with the total absorptions for individual component lines.[4]

The half-width α of a collision-broadened spectral line is proportional to the molecular collision frequency. From kinetic theory[5] it can be shown that

$$\alpha = \frac{1}{4\pi} \sum_i N_i (D_{a,i})^2 \left[2\pi kT \left(\frac{1}{m_a} + \frac{1}{m_i} \right) \right]^{1/2}, \qquad (2)$$

where N_i is the number of molecules of the ith type per unit volume, $D_{a,i}$ is the sum of the optical collision diameters of the absorbing molecule and a molecule of the ith type, m_a is the mass of the absorbing molecule, and m_i the mass of molecule of the ith type.

The present paper gives the results obtained in an experimental study of the relative abilities of various molecules to broaden the infrared absorption lines of atmospheric gases such as N_2O, CO, CH_4, CO_2, and H_2O vapor. In the course of the experimental work, various binary mixtures of absorbing gases and "broadening gases" were employed. For binary mixtures,

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Eq. (2) reduces to

$$\alpha = \frac{1}{4\pi}(2\pi kT)^{1/2}\left[N_a(D_{a,a})^2\left(\frac{2}{m_a}\right)^{1/2} + N_b(D_{a,b})^2\left(\frac{m_a + m_b}{m_a m_b}\right)\right]^{1/2}, \quad (3)$$

where the subscripts a and b refer to absorbing and broadening gases, respectively. Substitution for N_a and N_b in terms of the partial pressures p_a and p_b gives

$$\alpha = \frac{1}{4\pi}\left(\frac{2\pi}{kT}\right)^{1/2}(C_{a,a}p_a + C_{a,b}p_b), \quad (4)$$

where $C_{a,a}$ and $C_{a,b}$ are constants involving the masses and optical collision diameters of the absorbing and broadening gases. Recalling that the total pressure $P = p_a + p_b$, one may obtain from (4) an expression for α in terms of P and p_a:

$$\alpha = \frac{1}{4\pi}\left(\frac{2\pi}{kT}\right)^{1/2} C_{a,b}\left[(p_a + p_b) + \left(\frac{C_{a,a}}{C_{a,b}} - 1\right)p_a\right]$$
$$= \frac{1}{4\pi}\left(\frac{2\pi}{kT}\right)^{1/2} C_{a,b}[P + (B-1)p_a], \quad (5)$$

where $B = C_{a,a}/C_{a,b}$ is called the self-broadening coefficient of the absorbing gas and represents the ratio of the "self-broadening ability" of the absorbing gas to the "broadening ability" of the broadening gas, which was N_2 in the present study. The term in brackets in (5) is called the equivalent pressure P_e of the example

$$P_e = P + (B-1)p, \quad (6)$$

where P is the total pressure of the sample and p is the partial pressure of the absorbing gas in binary mixture with N_2.

It should be remarked that the theory involved in the above discussion may be expected to apply to lines whose width is determined primarily by collision broadening; it is not applicable to extremely low pressures, for which natural widths and Doppler broadening are dominant, or to extremely high pressures, at which absorption *during* collision or "close approach" leads to Stark effects and asymmetrical pressure shifts. Experimental studies to be reported later have shown that the total absorption $\int A(\nu)d\nu$ for an entire band in the infrared can be expressed in terms of the two parameters P_e and w for the range of pressures in which collision broadening is dominant.

Self-Broadening Coefficients

The experimental determination of the self-broadening coefficient B involves a study of the transmission of radiation through cells of different length in which the absorber concentration w is the same. The sample in the short cell, called the "reference cell," consists of a pure sample of the absorbing gas; in view of (6) the equivalent pressure in the reference cell is $P_e = Bp^{ref}$. The sample in the longer cell, called the "sample cell," initially consists of the pure absorber at the partial pressure required to produce an absorber concentration equal to that in the reference cell. Various amounts of dry nitrogen N_2 are then added to produce equivalent pressures $P_e = p_{N_2} + Bp$, where p_{N_2} is the partial pressure of the nitrogen. For the situation in which the absorptions in the sample and reference cells are most nearly equal, it is assumed that the equivalent pressures in the two cells are the same. The value of the self-broadening coefficient B can then be determined from the relation

$$B = p_{N_2}/(p^{ref} - p). \quad (7)$$

In some experiments the reference cell also contains N_2 at a partial pressure $p_{N_2}{}^{ref}$; for this situation the expression for B becomes:

$$B = (p_{N_2} - p_{N_2}{}^{ref})/(p^{ref} - p). \quad (7')$$

The value of B was determined for several absorption bands by making use of the double-beam feature of a Perkin-Elmer Model 21 spectrometer. In some cases, a 1.55-cm cell was used in the reference beam with a 6.35-cm cell in the sample beam; in other cases a 400-cm reference cell was used in conjunction with an 800-cm or a 1600-cm sample cell. Typical comparisons obtained with the double-beam spectrometer are shown in the upper panel of Fig. 1. The spectral record gives the ratio of the transmission of the sample T_{sam} to that of the reference T_{ref}; the dashed line represents the recorder pen position when the two beams were "balanced" with $T_{sam} = T_{ref}$. It is seen that the ratio T_{sam}/T_{ref} decreases with increasing pressure in the sample cell, as would be expected, and that some curves are above the balance line for some frequencies and below the balance line for other frequencies. The pressure corresponding to balance at any given frequency can be determined by interpolation between curves lying above and below the balance line.

Since the values of p_{N_2} corresponding to balance vary with frequency, it is apparent that the value of B varies throughout the band. Points giving the experimentally determined values of B are shown in the center panel of Fig. 1. The corresponding ratios of collision diameters are indicated on the right-hand ordinate scale; these were determined from the relation

$$B = \left(\frac{2m_b}{m_a + m_b}\right)^{1/2}\left(\frac{D_{a,a}}{D_{a,b}}\right)^2, \quad (8)$$

where the subscript a refers to the absorbing gas (N_2O) and the subscript b refers to the broadening gas (N_2). A typical absorption curve of an N_2O sample is shown in the lower panel of Fig. 1 in order that the "structure" of the absorption curve can be correlated with the "structure" of the curve relating B to frequency.

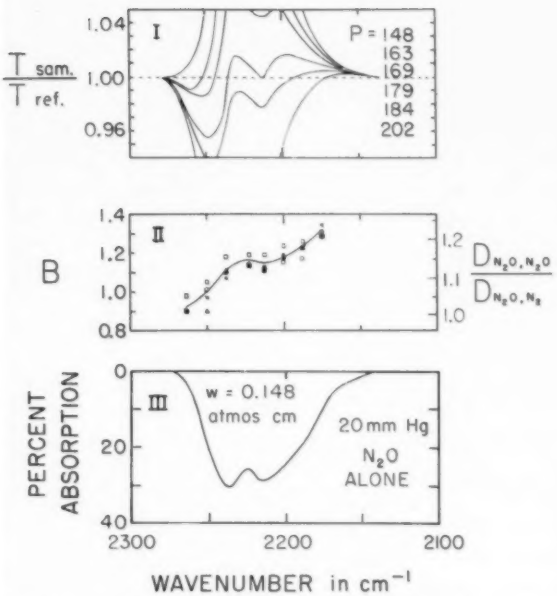

Fig. 1. The self-broadening coefficient B for the 2224 cm^{-1} N_2O band. I—Spectra obtained with $w = 0.30$ atm cm of N_2O in both reference and sample cells; total pressure in reference cell = 164 mm Hg. Total pressure in sample cell for each spectrum is indicated. II—Plot of B and collision cross section ratio. The four different geometrical points correspond to the results of the set of spectra shown in I as well as to three other sets of samples having different values of w. III—A typical absorption curve which is shown for comparison.

Studies similar to the one summarized in Fig. 1 were made for various absorption bands of CH_4, CO, CO_2, and H_2O vapor as well as for other N_2O bands. Various cell lengths and absorber concentrations were used. A single-beam Perkin-Elmer Model 99 spectrometer mounted in a vacuum tank was used for certain bands of CO_2 and H_2O vapor in order to eliminate possible errors due to the effects of atmospheric absorption. For these bands the value of B was determined by comparing the total absorption of samples having the same value of absorber concentration, but in cells of different lengths.

Much current interest in atmospheric transmission is involved with the total absorption associated with various bands rather than with absorption at isolated frequencies. It was therefore desirable to determine nominal values of B for various entire bands of different gases. Nominal values of B are listed in Table I and represent weighted averages of B, with extra weight given to frequency ranges at which absorption is greatest. It is believed that the listed values of B are accurate to $\pm 6\%$ when applied to entire bands, except in the case of H_2O vapor, for which the uncertainty is $\pm 25\%$. Possible adsorption effects along with the limited range of partial pressures of H_2O vapor contribute to the large uncertainty given to the B value for H_2O vapor.

Included in Table I are also values of B obtained by earlier investigators.[5] Agreement of the values obtained by different methods is fair. Some of the results listed by other investigators are based on studies of the total absorption of single lines; other results listed are based on measured transmission at one or more frequencies within absorption bands.

Foreign Gas Broadening

The relative line broadening abilities of two non-absorbing gases can be found by comparing the partial pressures required to produce equal total absorption $\int A(\nu)d\nu$ when the two gases are added to equal samples of an absorbing gas. The method used in the present work is illustrated in Fig. 2. A sample of CO having a partial pressure of 100 mm Hg was introduced into a 6.35-cm cell; the total absorption of the

Table I. Self-Broadening Coefficients

Band	Investigator	Self-broadening coefficient B
N_2O		
2224 cm^{-1}, 1285 cm^{-1}, and 1167 cm^{-1}	Present study	1.12 ± 0.07
1285 cm^{-1}	Goody and Wormell	1.27 ± 0.04
1167 cm^{-1}	Goody and Wormell	1.35 ± 0.07
2224 cm^{-1}	Cross and Daniels	1.29
CO		
2143 cm^{-1}	Present study	1.02 ± 0.06
4260 cm^{-1}	Present study	1.08 ± 0.06
CH_4		
3020 cm^{-1}	Present study	1.30 ± 0.08
1306 cm^{-1}	Present study	1.38 ± 0.08
CO_2		
3716 cm^{-1}, 3609 cm^{-1}, 2350 cm^{-1}, 961 cm^{-1} bands, and the 875–495 cm^{-1} region	Present study	1.30 ± 0.08
Same CO_2 bands	Edwards	$2 + 0.5p$ (where p is CO_2 partial pressure in atmospheres)
H_2O		
5332 cm^{-1}, 3756 cm^{-1}, and 1595 cm^{-1}	Present Study	5 ± 1.5
20 micron region	Palmer	$11 - 6T$, where T is the fractional transmission
4025.4 cm^{-1} H_2O line	Vasilovsky and Neporant	6
4 lines in 500–600 cm^{-1} region	Izatt	3.6–5.5

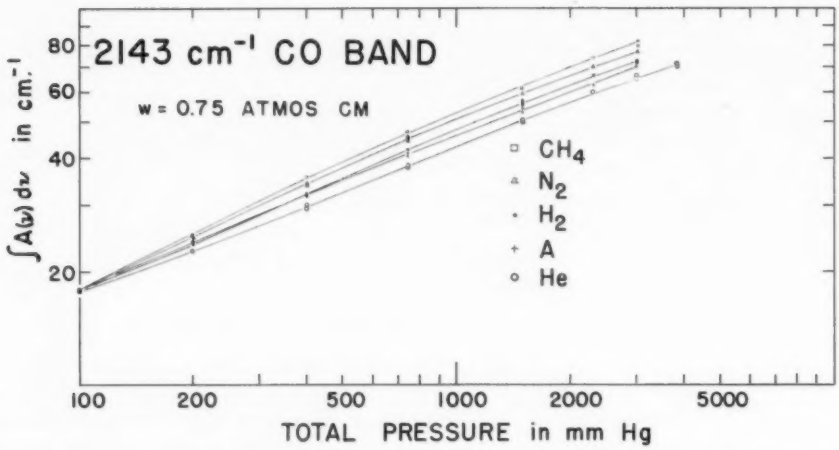

Fig. 2. Total absorption versus total pressure for 2143 cm^{-1} CO band. Partial pressure p of CO = 10 mm Hg.

2143-cm^{-1} band was measured and is represented by the point at the lower end of the curves in Fig. 2. One of the foreign gases, such as He, was then added to the cell; the total absorptions for He pressures of 200, 400, 760, 1500, and 3000 mm Hg were measured and plotted on the lower curve in Fig. 2. The same procedure was repeated for other foreign gases; great care was taken to start with the same quantity of CO in the absorption cell. From the curves in Fig. 2, it can be seen that with a sample containing CO and N_2 the total absorption is 50 cm^{-1} when the total pressure is 960 mm Hg; the same total absorption is obtained with a CO and He sample at a total pressure of 1450 mm Hg. Since the partial pressure of CO is 100 mm Hg in both cases, it can be concluded that 1350 mm Hg of He are required to produce the same broadening as 860 mm Hg of N_2.

A quantity called the relative *foreign broadening coefficient* F of a nonabsorbing gas b is defined by

$$F = p_{N_2}/p_b, \tag{9}$$

where p_b is the partial pressure of gas b required to give the same total absorption as that produced by a partial pressure p_{N_2} of nitrogen when the absorber concentration w is the same in the two samples. Thus, for the case of He cited in Fig. 2, $F = 860/1350 = 0.64$. Values of F for various foreign gases are listed in Table II for various absorbing gases; all values of F are referred to N_2 as in (9). Values of F for different values of w and different values of total absorption are nearly the same, and there is no significant variation of F for the ranges of total absorption and total pressure covered in the present work.

Also listed in Table II are ratios of the collision diameter ratios $D_{a,b}/D_{a,N_2}$ which are related to F by the expression

$$\frac{D_{a,b}}{D_{a,N_2}} = F^{1/2}\left[\left(\frac{28 + M_a}{M_b + M_a}\right)\frac{M_b}{28}\right]^{1/4}, \tag{10}$$

where M_a and M_b are the molecular weights of the absorbing and broadening gases, respectively.

Table II. Foreign-Broadening Coefficients and Relative Molecular Cross Sections

Absorber and band	Partial pressure of absorber[a] (mm Hg)	Total pressure range (mm Hg)	Broadener b	F[b] (mean)	$D_{a,b}/D_{b,N_2}$ (mean)
N_2O 2224 cm^{-1}	10	25–1000	He	0.73	0.58
			O_2	0.83	0.93
			A	0.78	0.93
			H_2	1.23	0.64
			CH_4	1.08	0.94
N_2O 1285 cm^{-1}	100	180–1000	He	0.70	0.57
			H_2	1.21	0.64
			A	0.83	0.96
			O_2	0.72	0.87
			CO_2	1.17	1.14
			CO	0.97	0.99
CO 2143 cm^{-1}	100	200–3000	He	0.64	0.56
			A	0.78	0.92
			H_2	0.85	0.56
			CH_4	1.12	0.98
CO_2 2350 cm^{-1}	50	80–700	He	0.59	0.52
			O_2	0.81	0.92
			H_2	1.17	0.62
			A	0.78	0.93
C_2H_6 3000 cm^{-1} bands	10	50–1000	He	0.52	0.51
CH_4 3020 cm^{-1}	50	100–2500	He	0.56	0.56
			A	0.82	0.93
			CO_2	1.25	1.15

[a] Cell length = 6.35 cm.
[b] Tabulated values of F are believed accurate to less than ±6%.

Some of the present values of collision diameter ratios can be compared with earlier results of others. Some years ago Cross and Daniels[5] studied the effects of He, H_2, O_2, and A on the absorption of N_2O *at a given frequency* in the region of its 2224-cm^{-1} band; their values of collision diameter ratios are approximately 7% higher than the present values, which are based on total absorption. Their values of collision diameter ratios for He and H_2 in CO are approximately 12% higher than the values obtained in the present work. There is fair agreement between the present results and those reported by Benesch and Elder,[6] who studied the effects of He, A, N_2, and CO_2 on the $J = 4 \rightarrow 5$ line of the 3020 cm^{-1} band of CH_4. Although the results of the two studies are reported in different forms, it would appear that they agree to within 10% for CO_2 and to within 5% for the other gases.

Since both the self-broadening coefficients B and the foreign-broadening coefficients F listed in the tables are referred to nitrogen, the equivalent pressure P_e for a sample consisting of several broadening gases can be written

$$P_e = Bp + p_{N_2} + \sum_i F_i p_{b_i}, \qquad (11)$$

where p is the partial pressure of the absorbing gas and F_i is the foreign-broadening coefficient of the ith broadening gas whose partial pressure is p_{b_i}. This equation is useful in studies of atmospheric gases. It has been demonstrated in work scheduled for early publication that at a given temperature the total absorption of a given band depends only on P_e and absorber concentration w.

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Future Issues

Each issue will specially feature one area of applied optics in addition to the usual contributed papers, shop and technical notes, reports of meetings, Letters to the Editor, book reviews, Meetings Calendar, and special columns. The feature subject of each issue will be the responsibility of one editor.

1962	July	**Optical Engineering**	Roderic M. Scott
	September	**Infrared**	John N. Howard
	November	**Ultraviolet**	—
1963	January	**Astronomy**	James G. Baker
	February	**Information Theory**	F. Dow Smith
	March	**Instrumentation**	W. L. Hyde
	April	**to be announced**	
	May	**Interferometry**	R. A. Woodson
	June	**to be announced**	
	July	**Spectroscopy**	Mary E. Warga
	August	**to be announced**	
	September	**Lens Design and Computers**	D. P. Feder

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Applied Optics

Letters to the Editor

Letters to the Editor should be addressed to the Editor, APPLIED OPTICS, 1155 16th St., N.W., Washington 6, D C.

Multiple-Pinhole Multiple-Beam Interferometric Observation of Flat Surfaces

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Recently Herriott[1] described a simple technique by which a group of optical flats for a Fabry-Perot interferometer could be tested quickly and easily. The method is to obtain Fizeau fringes of equal thickness[2] between the two flats to be tested. The flats are coated with a high reflecting material such as silver so that the transmission is a few percent. Normally, when Fizeau fringes are obtained, the distance between two successive fringes corresponds to a path difference of a half wavelength. In order to obtain high sensitivity, the distance between the fringes should be made as large as possible, i.e., reduce the angle between the flat surfaces as much as possible. The situation is illustrated in Fig. 1 of Herriott's paper.[1] The aperture of the flats is filled with three fringes, one at either end and one in the center. The intermediate space is not occupied by the fringes; and in order to see the over-all quality, these must be traversed across the surface. This was done by Saunders[3] by changing the air pressure, and a series of exposures at various pressure intervals results in the survey of the quality of the flats over the entire surface. The method used by Herriott[1] is essentially that, instead of using one wavelength, many wavelengths around a mean wavelength are used. Each wavelength gives rise to its own Fizeau fringes. The small changes in the wavelength are sufficient to shift the Fizeau fringe system of each wavelength and thus the fringe interval is reduced from half a wavelength to any fraction thereof. This situation is illustrated in Figs. 2, 3, and 5 of Herriott's paper.[1]

The object of the present note is to point out that the fringe interval could be reduced from half a wavelength to any desired fraction by another and probably simpler technique. In this technique a single wavelength is sufficient so that there is no need for a monochromator. Let us first consider a single pinhole on the axis of the collimator lens that gives a collimated beam which essentially strikes the pair of plates normally. This collimated beam on axis will give rise to its own Fizeau fringes when the two plates are inclined by a small angle. If now we place another pinhole which is off-axis with respect to the first one, this will give rise to its own Fizeau fringes which are displaced with respect to the original system. Let us suppose the separation of the plates at the center to be t_0, the angle of incidence of the collimated light θ, the order of interference n, and wavelength λ. Then the following relation is well known

$$2t_0 \cos\theta = n\lambda. \tag{1}$$

For the pinhole on-axis, θ is zero so that

$$2t_0 = n_0\lambda. \tag{2}$$

Let the pinhole off-axis be at a distance d from the axis and let f be the focal length of the collimating lens. Then (1) may be written as follows, neglecting higher powers of θ^2

$$2t_0\left(1 - \frac{d^2}{2f^2}\right) = n\lambda$$

or

$$(n_0 - n)\lambda = t_0\frac{d^2}{f^2} = t_0\theta^2. \tag{3}$$

Now if $(n_0 - n)$ is unity, the Fizeau fringe system due to the off-axis pinhole is shifted exactly one fringe with respect to the fringe system formed by the on-axis pinhole. Thus by inserting a series of pinholes between these two extremes, we obtain fringes of the Fizeau type with any desired fractional wavelength interval. Let us consider Eq. (3) and evaluate the relationship between t_0 and θ. For our purpose $(n_0 - n) = 1$ and so we have

$$t_0\theta^2 = \lambda. \tag{4}$$

From this, we see that the method depends on the finiteness of the value t_0. The smaller the value of t_0, the larger the value of θ should be. In order that we may have a reasonable value for θ, t_0 must be a few wavelengths of the light being used. Another point of interest that might be mentioned is that to obtain equal fringe intervals, the pinholes should be placed at unequal spacings. The law of spacing of these pinholes may be deduced from (3) as follows. Let N be number of the pinholes and let j denote the jth pinhole. Then the distance d_j of the jth pinhole from the axis of the lens is given by

$$d_j = f\sqrt{\frac{\lambda}{t_0}\left(\frac{j-1}{N}\right)}, \tag{5}$$

j being equal to 1 for the pinhole on axis. Thus for a given collimator lens and a given pinhole plate, the value of t_0 must be adjusted to the proper value. An alternate approach is to use a zoom lens for the collimator with a fixed pinhole plate and

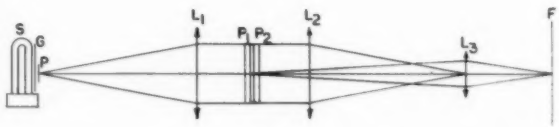

Fig. 1. Schematic diagram showing the arrangement of the various elements for testing flat surfaces in which the fringe interval of the Fizeau fringes is a fraction of half a wavelength of the light used. S—Low pressure mercury arc such as a germicidal lamp; G—5461 Å filter; P—plate with the pinholes; L_1—collimating lens; P_1, P_2—coated optical flats under test; L_2—focusing lens; L_3—field lens in whose plane the plate P is imaged; F—conjugate plane of P_1 and P_2 with respect to the lens L_3. On this plane the Fizeau fringes could be photographed by placing film.

fixed value of t_0. A schematic diagram showing the arrangement for obtaining the fringes described in the foregoing is shown in Fig. 1.

Using a variable separation Fabry-Perot interferometer available at the Institute of Optics, the conclusions arrived at in the foregoing have been verified and thus it is possible to obtain fringes of Fizeau type with fractional fringe intervals using the simple technique of multiple pinholes. This method may be considered as an alternate approach to that of Herriott[1] in obtaining the same final goal.

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A Wavelength Standard for Ultraviolet-Visible-Near Infrared Spectrophotometry

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Vandenbelt has recently proposed[1,2] that the spectrum of the oxide of the rare earth element holmium be used to calibrate the wavelength coordinate of recording spectrophotometers in the ultraviolet-visible. Our investigations confirm his judgment. We have therefore calibrated samples of the material against wavelength standards and are using the samples on a routine basis in our laboratory. Reported here are our spectra of holmium oxide both in solution in perchloric acid and as a suspension in glass. (The latter is available in commercial form from Corning Glass Works, Corning, N.Y., as glass No. 3130, or as a calibrated filter from the National Bureau of Standards.[3]) As can be seen from Figs. 1 and 2, the solution spectrum is sharper, and richer in lines. However, the glass is a more convenient material since it is permanent. In addition, it displays bands beyond the water cutoff in the near infrared.

Several thicknesses of the glass were prepared as samples, 2.7 mm being a preferable compromise. The spectrum of this sample is shown in Fig. 1. A comparison with Fig. 2 shows that the 240 mμ band was cut off by the transmission characteristics of the glass. This was true of all the glass samples we tested, but it is reported[4] that if the material is purchased from Corning as CS3-138, the band will be present. No variation in wavelength was observed among the six samples selected at random from a single 15 × 15 cm glass plate.

The solution used was 4% holmium oxide in 1.4 molar perchloric acid. The cell had an optical path of 1.5 cm. This arrangement, with air as a reference, provided sharp absorption bands and a low background level.

All measurements were made on a Perkin-Elmer Model 350 recording spectrophotometer. Since our ultimate intent was to use holmium oxide for calibrating the wavelength scale of recording spectrophotometers, accurate standards had to be used to check the wavelengths of the sample bands. Three materials were selected as wavelength standards:

1. The Hg emission spectrum[5] obtained from a GE OZ4 germicidal lamp was used over the range from 230 to 600 mμ. (The lamp was in series electrically with a 60 watt incandescent lamp, used as a ballast. The pair were operated at 115 volts, ac.) The majority of the emission lines were recorded using a spectral slit of less than 3 Å; no lines were obtained at spectral widths greater than 10 Å.
2. The H_2 emission spectrum[6] from the H_2 arc lamp used as the ultraviolet source in the instrument was used for the range from 500 to 660 mμ. The spectral slit width used was less than 5 Å.
3. Water vapor[6,7] was used as a wavelength standard in the near infrared region. The absorption of atmospheric water was run using the single beam mode.

Small portions of the spectra were scanned at the largest wavelength expansion available on the instrument. We recorded the spectrum of the test material, the spectrum of the suitable reference standard, and reference marks from the wavelength dial in succession. A smooth, continuous graph was drawn by plotting the location of the wavelength dial reference marks against wavelength. Small corrections to this curve were determined by plotting the band locations in the reference standard spectra. It was then possible to determine the wavelength of the holmium oxide bands by reference to the graph. This process is illustrated by Fig. 3 which shows one section of calibration of the holmium oxide solution in the region around 450 mμ. The wavelength accuracy was limited by the accuracy available in measuring the positions of the bands and by their width. Table I records the results for both solution and glass, along with experimental limits.

The data reported earlier[1,2] were simply the values taken from a number of test instruments. Since no reference standard was used, no particular credence was placed by the author in the wavelengths reported. In spite of that, our data for the solution agree quite well with ref. 2, except for the bands at 287.1, 485.8 mμ, and in the near infrared. The glass data showed better agreement[1] but significant variations occur at 419.6 mμ and 360.9 mμ in the ultraviolet spectrum.

Table I. Corrected Wavelength for Holmium Oxide Spectra

Band number	Wavelength (mμ) Solution	Glass
1	241.10 ± 0.05	—
2	249.7 ± 0.1	—
3	278.7 ± 0.1	279.37 ± 0.05
4	287.1 ± 0.1	287.5 ± 0.1
5	333.4 ± 0.1	333.7 ± 0.1
6	345.5 ± 0.1	—
7	361.5 ± 0.1	360.9 ± 0.1
8	385.4 ± 0.2	385.9 ± 0.2
9	416.3 ± 0.2	418.7 ± 0.2
10	450.8 ± 0.2	453.2 ± 0.2
11	452.3 ± 0.2	—
12	467.6 ± 0.2	460.0 ± 0.2
13	485.8 ± 0.2	484.5 ± 0.2
14	536.4 ± 0.2	536.2 ± 0.2
15	641.1 ± 0.2	637.5 ± 0.2
16	891 ± 1	—
17	1159 ± 1	1153 ± 1
18	1190 ± 1	1192 ± 1
19	—	1938 ± 2
20	—	2007 ± 2

* Now at Carnegie Institute of Technology, Pittsburgh, Pa.

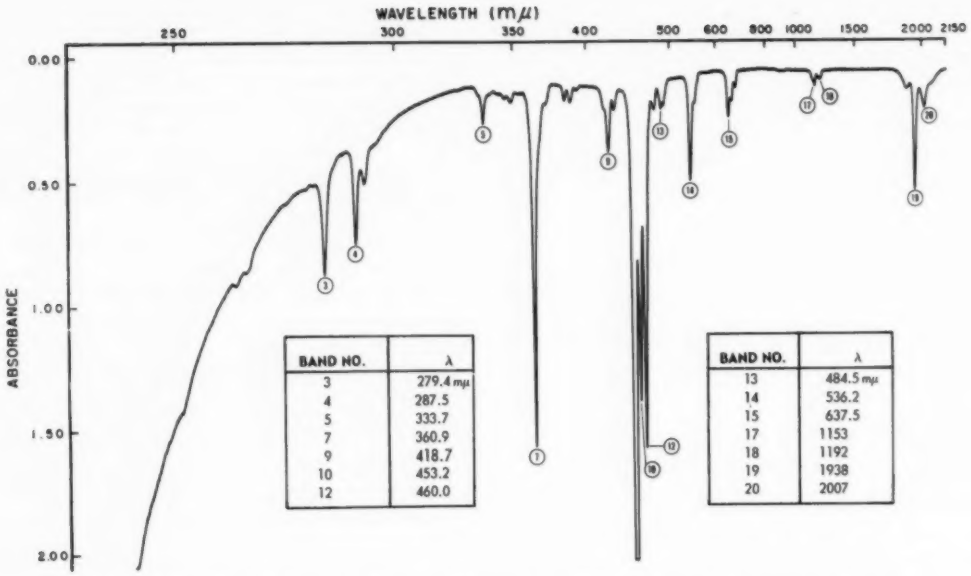

Fig. 1. The absorption of holmium oxide glass against air using the Model 350 spectrophotometer.

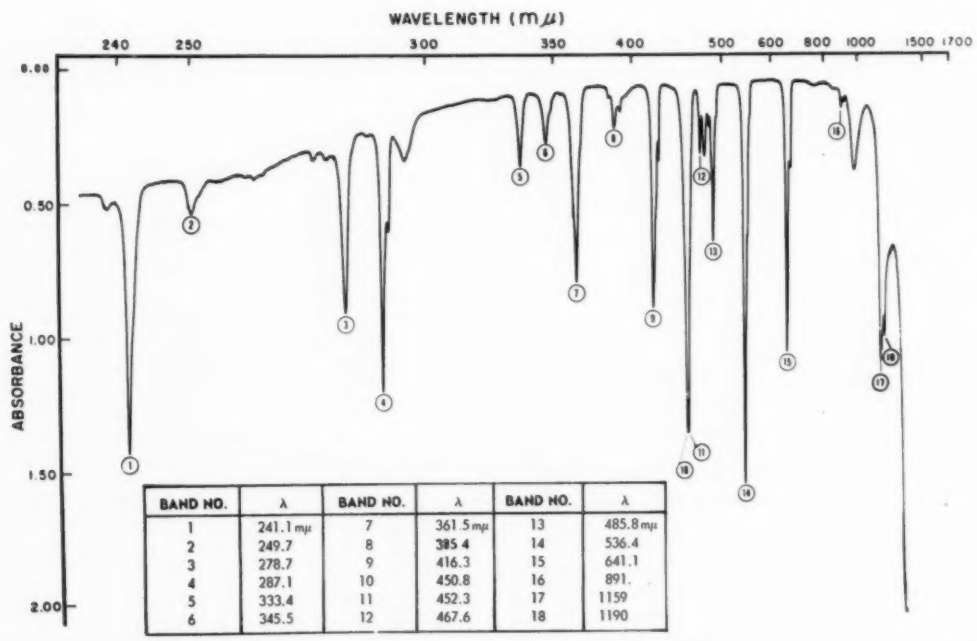

Fig. 2. The absorption of 4% holmium oxide solution in 1.4 molar perchloric acid. The spectrum was run against air on the Model 350 spectrophotometer in a 1.5-cm cell.

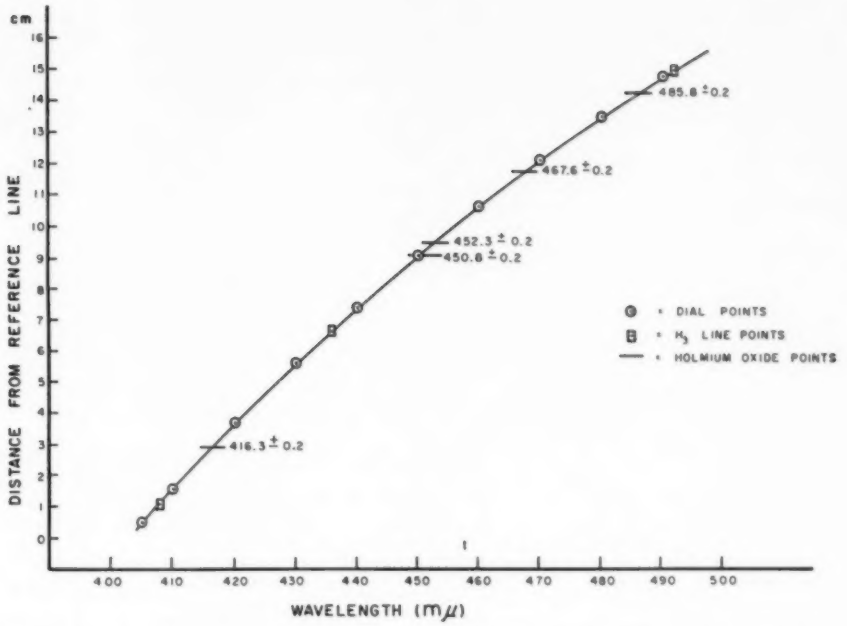

Fig. 3. Calibration curve for the holmium oxide solution spectrum in the 450-mμ region. Mercury emission calibration points are shown.

We observed significant variations in the transmittance of the glass samples with temperature though no variation was observed in the wavelength of the bands. A recent study[8] of the temperature dependence of a number of rare earth glasses is in agreement with our findings. Presumably, then, the temperature-related wavelength variation observed by Vandenbelt[1] was attributable to his instrument. The strong variations with temperature in the transmittance of most of the bands, however, make the glass undependable for photometric standards.

No change in shape or position of the bands was observed for any slit program routinely available on the test instruments in our laboratory. However, if either the solution or glass are used in instruments of very broad spectral bandpass, a significant error may result. We have recorded the spectrum of the glass sample at successively wider bandpass to determine where such errors will appear. The result of this work is recorded in Table II. On conventional quartz or silica prism instruments using photomultiplier detectors, the first band to be altered as the slit width is increased is the band at 536 mμ. If the glass is used routinely to test the wavelength accuracy of instruments, the same spectrum can be used to detect instruments of very poor resolution by observing the shape of this band.

Table II. Minimum Bandpass before Bands in the Glass Begin to Change Shape

Band number.	(mμ)	Bandpass (mμ)
9	418.7	4
10	453.2	7.5
12	460.0	5
13	484.5	4.5
14	536.2	6
15	637.5	12

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Some of the participants in the WMO Vienna August meetings including B. Haurwitz *Colorado,* J. London *Colorado,* W. Schüepp *Leopoldville,* H. G. Müller *Munich,* P. Bener *Davos,* J. H. Shaw *Ohio State,* J. N. Howard *GRD,* and E. V. Loewenstein *GRD*

Machine-Aided Selection of Optical Glasses for Two-Element, Three-Color Achromats

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Received 13 November 1961.

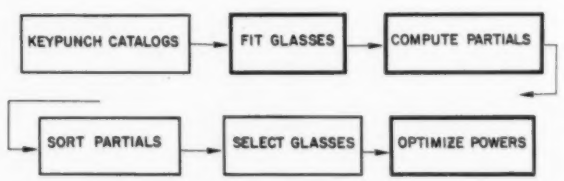
The work of Herzberger[1] and Stephens[2] dealing with the necessary conditions and optical glass selection needed to achieve four-color achromats stimulated our interest in seeking combinations of glasses that would give four-color correction for longitudinal chromatic aberration. We have not been successful in finding such a pair of glasses, but we have as a result found several glass pairs which give three-color correction. These may prove to be of some value to astronomers. The general methods used to find these combinations are discussed herein.

The methods that we have used are, in principle, those of Stephens[2] but we have adapted them for use in our high-speed digital computers (IBM 7090, Philco 2000).

The first step (see Fig. 1) is to transfer the index of refraction data from the glass manufacturers' catalogs to punched cards. The identification of the glass and manufacturer are put on the card, and weathering, acid, availability, etc., codes can be included as desired. This process need be done only once, except where errors need to be corrected

Secondly, the index data are fitted by the method of least squares to Herzberger's "Universal Function" formula to minimize the effects of measured and typographical errors in the glass tables. The form of the dispersion formula currently used is shown at the bottom of Fig. 1. This program produces a deck of cards which constitutes a "Universal Glass Catalog." Each card of the deck has the four fitted indices for the glass at the A', C, F, and h Fraunhofer lines of the spectrum and the identification of the manufacturer and glass type. The durability codes may be included, and additional comments can be added to the cards at a later date as desired. This fitting step need be done only once also, unless it is desired to fit data to some other formula such as has been done by Sutton and Stavroudis.[3]

The third step is to compute from these fitted indices the reciprocal dispersion and whatever partial dispersions are desired. Since the interpolation formula above is used for finding the index at any wavelength, the dispersions can be found for any wavelength within the region of validity of the particular interpolation formula used. This fact should prove to be of value since the best partials to be examined will depend on the wavelength region in which the residual spectrum is to be minimized. If the region from C to F light is not included in the region of primary interest, a reciprocal dispersion based on wavelengths in the region of interest should lead to better results. This arises because the relative powers of the elements depend on dispersion which is a function of wavelength and, therefore, the region to be achromatized.



$$n(\lambda) = B_{A'}(\lambda)\, n_{A'} + B_C(\lambda)\, n_C + B_F(\lambda)\, n_F + B_h(\lambda)\, n_h$$

Fig. 1. The steps in the procedure for selecting two-element, three-color achromats. The steps in heavier outline are currently done on a high-speed computer (IBM 7090). The dispersion formula currently used in the glass fitting operation is shown below the block diagram.

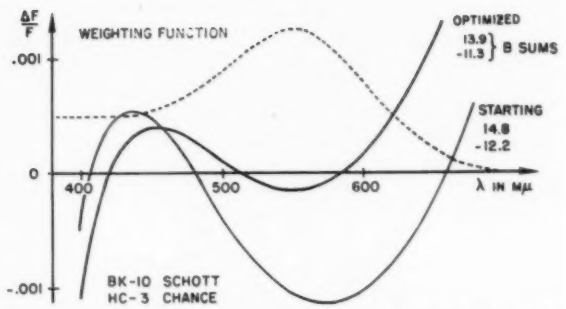


Fig. 2. The normalized change in focal length is plotted as a function of wavelength for a pair of glasses before and after being optimized with respect to the weighting function shown.

The computed dispersions are punched out by the computer with the same identification data that appear on the index catalog cards. The data from these cards could then be plotted on the three view graphs that Stephens described for the selection of three- or four-element, four-color achromats. However, if one is searching only for two-element combinations, the problem becomes well suited to the facilities of a modern computing laboratory.

The cards are sorted, in the fourth step, by an off line card sorter which puts one of the partial dispersions in ascending order. The ordered deck is then listed out by an off line printer. Table 1 shows a small sample of such a listing.

Table 1. A Few Lines from the List of Dispersions Ordered with Respect to the *e*-C Partials[a]

$\nu = \frac{n_d - 1}{n_F - n_C}$	$P = \frac{n_h - n_C}{n_F - n_C}$	$Q = \frac{n_{1.014} - n_C}{n_F - n_C}$	$R = \frac{n_e - n_C}{n_E - n_C}$	Identification
63.386	1.9775	0.85542	0.544502	Chance LBC-1
63.972	1.9771	0.85945	0.544694	Chance BSC-3
67.325	1.9797	0.86792	0.544796	Schott FK-6
50.677	2.0185	0.95544	0.544840	Hayward CF-2
64.273	1.9729	0.85559	0.544909	Chance BSC-1
64.273	1.9782	0.87167	0.545066	Schott BK-7

[a] The definitions of the dispersions are shown above each column.

The fifth step currently utilizes the designer, although this operation could be programmed if it were deemed advisable. One scans the listing to find glasses whose reciprocal dispersions are sufficiently different to give a practical combination and whose partial dispersions are nearly the same, so that these glasses will give rise to a reduced secondary spectrum. If a pair of glasses with significantly different reciprocal dispersions has identical partial dispersions for one of the partials, the thin lens combinations of these glasses would be corrected for three colors. The difference in the partials indicates the residuals of color at those wavelengths for which the partials were computed. A pair of glasses may provide three-color correction even though the particular partials computed are not identical; some other wavelengths may be corrected. However, if the differences in

the computed partials are large, the correction for three colors will be poor (even if it exists) because of residuals between the corrected wavelengths.

The sixth step is performed after promising pairs of glasses have been chosen by the previous step. The "Universal Catalog" index cards for these pairs of glasses are fed into a program which computes the error in focal length divided by the focal length as a function of wavelength for as many wavelengths as desired. The ratio of the powers of the two elements is then varied, and the optimal powers are found by a convergent procedure similar to that described by Meiron and Volinez.[4] Figure 2 shows an example of the residual longitudinal chromatic aberration of a glass pair before and after optimization of lens powers. A number representing the merit of the resulting combination with respect to residual spectrum is produced. The various pairs can then be compared by their merit numbers and the powers and durabilities of their elements.

Our experience to date is similar to that of earlier workers in that we have found that the durability and desirability of the glasses of greatest interest for two-element, three-color achromats are almost in inverse proportion to their ability to eliminate secondary longitudinal chromatic aberration.

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Abac Chart for Fast Calculation of the Absorption and Reflection Coefficients

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Simultaneous transmission and reflection measurements on a thick absorbent layer permit one to obtain the absorption and reflection coefficients. A fast calculation is proposed by using a double coordinate system abac chart.

The Drude theory[1] relates the reflection index n and the extinction coefficient k to the absorption coefficient K for a given wavelength, and the reflection coefficient r on the surface of an absorbent material by the equations:

$$r = \frac{(n-1)^2 + k^2}{(n+1)^2 + k^2}, \tag{1}$$

$$K = \frac{4\pi k}{\lambda}. \tag{2}$$

For an absorbent material it is convenient to make the measurements by means of a thick homogeneous layer with plane parallel faces illuminated by parallel light under normal incidence.

Under these conditions, multiple reflections are produced in the interior of the sample. The resultant intensity due to the contributions of all these reflections must be computed. Czerny[2] and Barnes and Czerny[3] have shown that the measured transmittance T and the reflectance R can be obtained by the formulas:

$$T = \frac{(1-r)^2 + 4r\sin^2\psi}{(e^{2\pi kd/\lambda} - re^{-2\pi kd/\lambda})^2 + 4r\sin^2[(2\pi nd/\lambda) + \psi]}, \tag{3}$$

and

$$R = r\,\frac{(e^{2\pi kd/\lambda} - e^{-2\pi kd/\lambda})^2 + 4\sin^2(2\pi nd/\lambda)}{(e^{2\pi kd/\lambda} - re^{-2\pi kd/\lambda})^2 + 4r\sin^2[(2\pi nd/\lambda) + \psi]}, \tag{4}$$

on introducing

$$\tan\psi = \frac{2k}{n^2 + k^2 - 1}, \tag{5}$$

where d is the thickness of the layer.

Fan and Becker[4] have reduced Eqs. (3) and (4), for the case of thick layer, by taking the average of the number of waves, d/λ to

$$T = \frac{(1-r)^2 + 4r\sin^2\psi}{e^{Kd} - r^2e^{-Kd}},$$

which is

$$T = \frac{(1-r)^2e^{-Kd}}{1 - r^2e^{-2Kd}}, \tag{6}$$

for not very absorbent layers. Similarly, one obtains

$$R = r(1 + Te^{-Kd}). \tag{7}$$

The formulas (6) and (7) can also be obtained directly by summing up the intensities due to the contributions of all the multiple reflections on the faces of the layer.

A calculation of the optical constants requires, first of all, the solution of Eqs. (6) and (7) in order to obtain r and K. Replacing r by its value in Eq. (6) one can solve the third-degree equation

$$(e^{-Kd})^3 + \left[\left(\frac{1-R}{T}\right)^2 - 1 + \frac{1}{T^2}\right]T(e^{-Kd})^2 + \left[\left(\frac{1-R}{T}\right)^2 - 2\right]e^{-Kd} - \frac{1}{T} = 0. \tag{8}$$

This equation can be solved for example by the method of Cardano. The calculations are long and painful. Besides, it is difficult to use them for the relating of systematically experimental measurements. Consequently, it is preferable to proceed by graphic solution.

The curves giving T and R for constant values of Kd and r have been traced (Fig. 1). We have taken a sufficient number of values for Kd and r in Eqs. (6) and (7) in order to permit easy interpolation.

Taking, on the abac chart, a point defined by its coordinates T and R, it is easy to read its coordinates in the system e^{-Kd}, r. Thus, Eq. (8) has been solved.

This method of graphic solution is valid only when the error introduced by the trace and the interpolation of the coordinates of points is small in comparison with the error on the experimental values of T and R. This is usually the case.

It has been concluded that the proposed abac chart permits one to obtain rapidly the transmission and the reflection coefficients of thick layers. Its usefulness is evident in the systematic study of the optical properties of such materials as semiconductors, which are neither perfectly transparent nor opaque, and which it

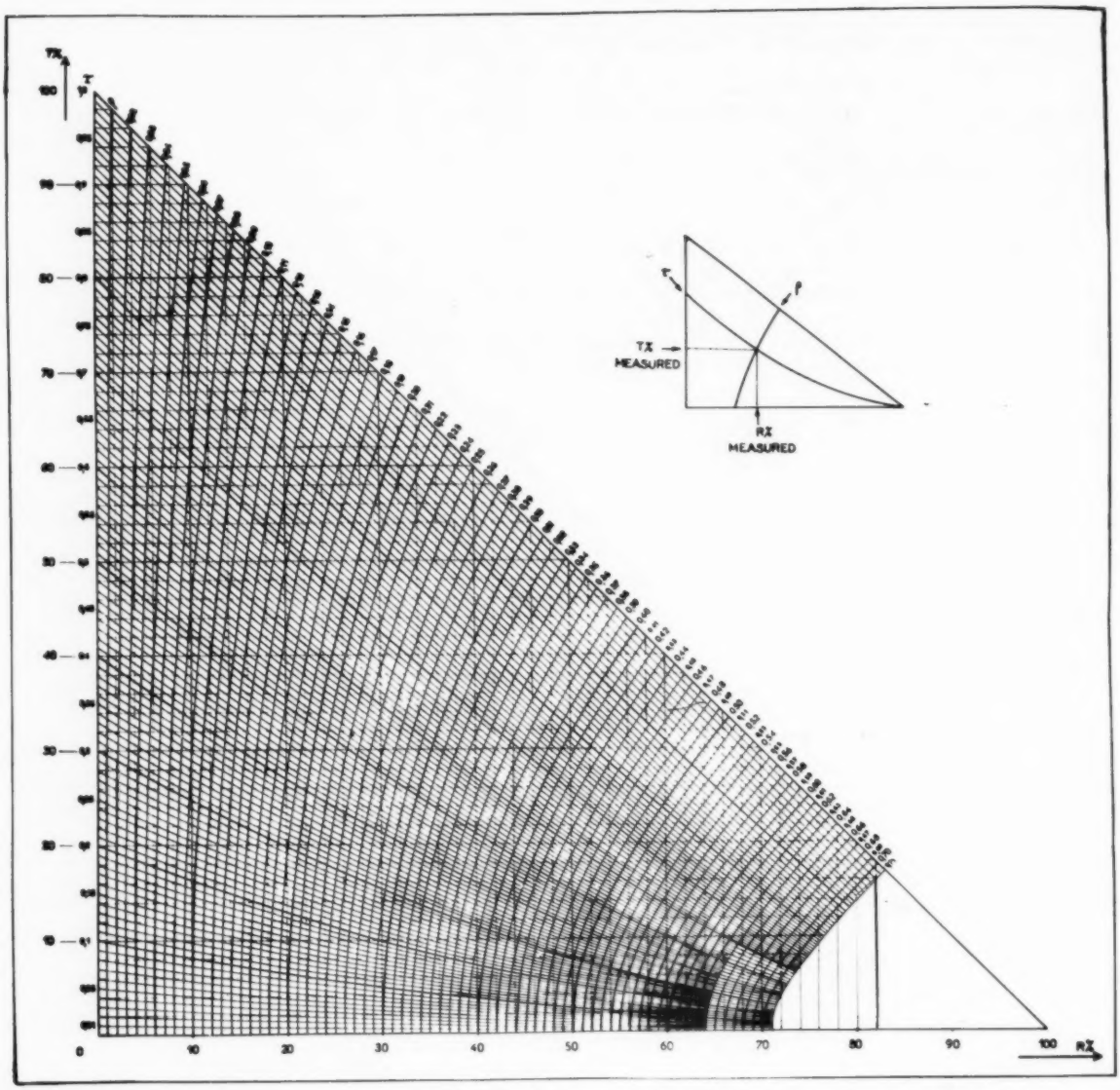

Fig. 1. The abac chart. Here $\rho = r$ and $\tau = e^{-Kd}$. In this figure T runs from 0 to 100%, R runs from 0 to 100%, $\tau = e^{-Kd}$ runs from 0.01 to 1.0 and $\rho = r$ runs from 0.01 to 0.71.

is difficult to obtain in homogeneous volumes great enough to permit one to cut prisms in them, and for which the absorption coefficient is related to important properties such as the nature and the concentration of the impurities.

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Optical Method for Resolving the Fourier Component of a Signal Periodic or Aperiodic in Time

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The theory of imperfect diffraction gratings has been well developed.[1] It is the purpose of this note to describe a simple optical technique based on this theory that has been employed in the frequency analysis of a time-varying electrical signal of several octaves bandwidth.

The signal to be analyzed is used to produce an optical diffraction grating in which the incremental transmitted amplitude is proportional to the instantaneous signal amplitude. The fabrication of such a grating can be achieved by a photographic process in which a slit, illuminated by an intensity modulated light source, is imaged on a film transported at a constant velocity in a direction perpendicular to that of the slit. This operation, similar to the "variable density" method of recording sound on movie film, differs from the latter in that the film is processed to have an over-all gamma of 0.5 instead of 1.0, since amplitude and not intensity proportionality is required between the input signal

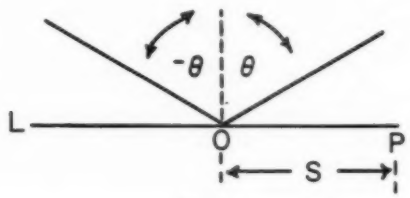

Fig. 1.

amplitude (which intensity modulates the exposing light source) and the transmitted light in the processed grating.

The plane grating thus formed is illuminated normally with parallel monochromatic light and the resulting Fraunhofer diffraction pattern is equivalent to the power spectrum of the original signal that produced the grating, and if the amplitude information has been faithfully preserved in the grating, only those orders of spectra will occur that correspond to harmonics actually present in the input signal. Thus, even though the band of interest may include several octaves, there will not be ambiguity caused by "overlapping of orders."

A brief argument showing the equivalence between the Fraunhofer diffraction pattern and the Fourier analysis of the wave shape producing the grating is shown in Fig. 1. Consider the standing wave system produced along line L, as the result of equal unit amplitude plane waves of wavelength λ arriving along directions $\pm\theta$ with respect to the line normal, and phased so that a maximum occurs at point O.

From a simple trigonometric relation it is apparent that the phase difference between points O and P for the wave train arriving from angle θ is $\phi+ = (2\pi s/\lambda)\sin\theta$ and for the wave train arriving from $-\theta$ is $\phi- = (2\pi s/\lambda)\sin(-\theta) = -\phi+$.

The resulting symmetric phasor diagram (Fig. 2) indicates that the amplitude of the resultant at point P is $A_r = 2\cos\phi+ = 2\cos[(2\pi S/\lambda)\sin\theta]$. Additionally, it is obvious because of the symmetry that the resultant is either in phase with or differs in phase by π radians with the phase of the resultant at point O, depending on the value of ϕ.

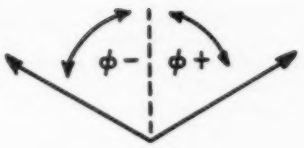

Fig. 2.

For a given θ and a given λ, it can then be considered that the phase of the resultant along L is instantaneously everywhere the same and that the amplitude varies sinusoidally along the length L, the phase inversions being produced when the amplitude has a negative value.

By reciprocity, if a grating having an amplitude transmission characteristic that varies sinusoidally along its length (including the necessary phase inversions) is normally illuminated with parallel light of wavelength λ so that all points along the grating are excited in phase, then the light energy will be diffracted to the angles $\pm\theta$ alone. Thus, a grating of this description will only produce a first-order spectrum.

Since it is possible to produce different space periodicities in the standing wave pattern by changing θ (λ remaining constant), it is possible to synthesize an arbitrary wave shape, periodic or not, by supplying energy along the various angles that are necessary to produce its Fourier components, discrete or continuous. Conversely, an arbitrary wave shape can be analyzed by observing the direction of the diffracted energy.

If we wish to eliminate the need for providing phase reversal in the construction of the grating, as would be required if the amplitude transmittance were to be directly proportional to a bipolar signal, we can do so by adding a dc term to the original signal producing the grating of sufficient magnitude that the expression for amplitude at any point never becomes negative.

Let us again consider formation of standing waves along L but in addition to the wave trains incident along $\pm\theta$ let a wave train be incident along the normal whose amplitude is twice that of either signal arriving from $\pm\theta$, and again permit this to be adjusted so that at point O it is in phase coincidence with the other wave trains.

From the phasor diagram (Fig. 3) it can be seen that the phase along L is instantaneously the same at all points and that the amplitude $A_r = 2 + 2\cos[(2\pi s/\lambda)\sin\theta]$ which never becomes negative. In this case the standing wave amplitude varies sinusoidally but has a "dc displacement." If a grating is constructed to be equivalent to this standing wave pattern, phase reversals are now not necessary and the dc displacement gives rise to the zero-order spectrum or to energy directed along the normal to the grating.

In the case just analyzed the "dc component" was as low as it could be without having negative values of amplitude. If the value of the "dc component" is greater than this, more energy would be directed into the zero-order spectrum but the relationships between the other components of the spectrum would remain unchanged. The amplitude of the zero-order spectrum is

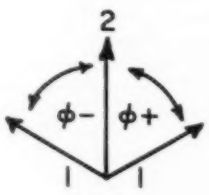

Fig. 3.

thus equivalent to the amplitude of the constant term in the Fourier analysis.

At this laboratory, this technique is employed with frequencies and film transport velocities that result in gratings that do not exceed about 32 lines per millimeter. Kodak Plus-X 35 mm film is used presently although Kodak Panatomic-X would permit closer grating spacings at the expense of requiring increased photographic exposures. The light source used in making the diffraction pictures is a sodium vapor lamp, and the optics consist of an unmodified Kirchhoff-Bunsen spectrograph.

A qualitative investigation was made to determine the degree of nonlinearity in the photographic process. A grating was constructed employing two nonharmonically related sine waves as input. While the diffraction pattern clearly showed the presence of these frequencies, the presence of the cross-modulation products (sum and difference frequencies) was barely perceptible, although these lay well within the system passband. Additionally, a sine wave grating was observed to produce a very strong first-order spectrum while higher-order spectra were not observed at all. It should be stated that these experiments were rather crude and that no great control was exercised on the photographic process.

As a corollary, it may be possible to investigate film transfer characteristics by this process (i.e., by measuring the amplitude of generated harmonics and cross-modulation products).

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Observation of Quasi c.w. Operation of an Optical Ruby Maser

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The purpose of this letter is to describe some of the results of experiments on ruby optical masers, although the theory advanced to explain these results can be applied equally as well to other types of optical masers. These experiments have led to the achievement of quasi c.w. operation whereby all the spikes in the ruby laser output have been eliminated.

Depending upon the pump duration and intensity of the radiation, the output pulse of the ruby laser lasts anywhere from 100 μsec to a few milliseconds. This pulse usually consists of a series of spikes which have different amplitudes and occur at different times. The formation and the frequency of occurrence of these spikes can, to some degree, be controlled by the following parameters, namely, the temperature of the ruby, the characteristics of the pump radiation, and the feedback mechanism used.

Consider an active medium such as Cr^{3+} in Al_2O_3, confined in a comparatively thin rod, and, moreover, consider this system to be pumped with a light source of frequency distribution $U(\nu, t)$ per square centimeter. To have stimulated emission in this system, $\Delta N = N_2 - N_1$ has to be greater than a certain number C, where N_1 and N_2 are the density of atoms in the energy states one and two.[1,2] This number depends upon the geometry of the rod, its temperature, and the amount of feedback provided by the reflective coatings at the ends of the ruby rod. This number can be found experimentally; for example, for a rod 6.25 cm long and 6 mm in diameter, having its flat ends parallel to within 6 sec of arc with no coatings at either end and operated at liquid nitrogen temperature, we find that C must be approximately 8.3×10^{18}/cm^3 to have laser action.

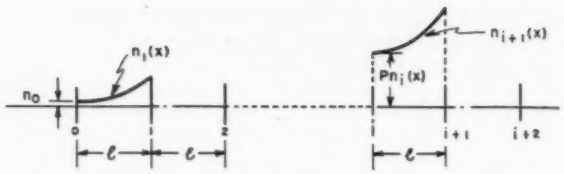

Fig. 1. A model representing a Fabry-Perot interferometer type laser.

Consider a cooled system operating in only a few of the frequency modes,[2] then if n_0 photons having a frequency ν_{12} are emitted at $x = 0$ in a direction perpendicular to the end surfaces, after a distance dx the change in this number would be

$$d^2n(x, t) = \Delta N(x) W_{12}(x) A\,dx\,dt. \tag{1}$$

A similar expression would apply for each of the remaining frequency modes. $W_{12}(x)$ is the transition probability and is given by

$$W_{12}(x) = kM_{12}n(x).$$

$n(x)$ is the number of photons at x, dt is the time interval for the photons to travel the distance dx, A is the cross sectional area of the rod, M_{12} is the matrix element for the transition from state two to state one, and k is a constant. Integrating (1) with respect to time, we obtain

$$dn = \Delta N(x) k M_{12} n(x) A \frac{x}{u}\,dx$$

where u is the velocity of light in the medium. Integrating again, we have

$$n(x) = n_0 \exp\left(\int^x \Delta N(x') k M_{12} A \frac{x'}{u} dx'\right). \tag{2}$$

The above equation gives the number of photons in the rod after traveling a distance x.

A simple model can illustrate the effect of the feedback on the frequency and the amplitude of the spikes. Consider the reflectivity of the ruby at either end to be ρ; then the mth reflection will feed back ρn_m photons into the ruby. We can represent this system by an array of filters each having a transmittance ρ and separated from each other by a distance corresponding to the length of the ruby (see Fig. 1). The number of photons traveling in the x-direction after having passed the ith filter would then be given by

$$n_i(x) = [n_1(l) n_2(2l) \ldots n_{i-1}(il-l)]\,\rho^{i-1} \times \exp\left(\int_{il}^x \Delta N_i(x') k M_{12} \frac{x'}{u}\,dx'\right), \tag{3}$$

where

$$(i-1)l \leqslant x \leqslant il,$$

$$\Delta N_i(x) = \Delta N_{i-1}(x) - (1-\rho) n_{i-1}(x) + \frac{N_2}{\tau_{23}}\delta t - \frac{N_2}{\tau_{21}}\delta t \tag{4}$$

and

$$\delta t = l/u,$$

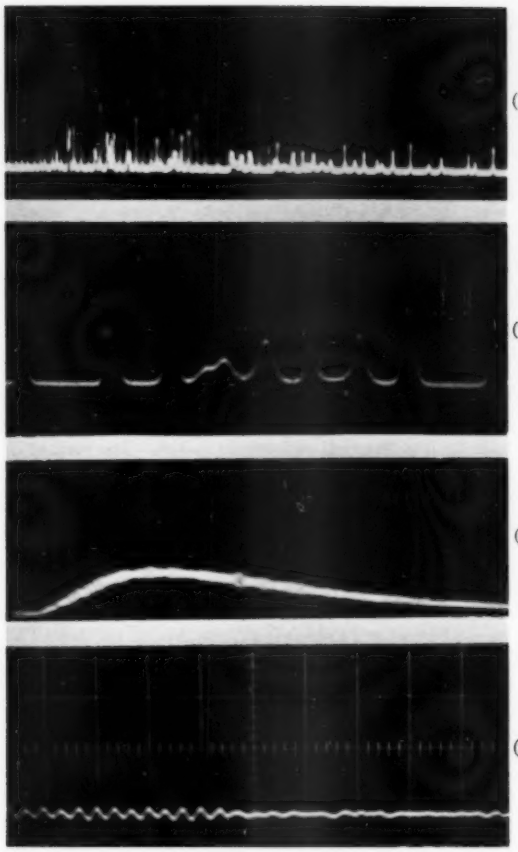

Fig. 2. (a) Room temperature, 50μsec/cm sweep. (b) Room temperature, portion of (a), 2μsec/cm sweep. (c) Liquid nitrogen temperature, 50μsec/cm sweep. (d) Liquid nitrogen temperature, portion of (c), 1μsec/cm sweep.

where τ_{21} is the spontaneous emission lifetime from state two to state one, τ_{32} is the thermal relaxation lifetime from state three to state two, and N_3 is the population density of the third state. To include the effect of the pump light, one can show, for a thin uniformly illuminated rod, that

$$\frac{N_3}{\tau_{32}} = \int_0^\infty d\nu\, u(\nu, t)\sigma_{13}(\nu)(N_1 - N_3)\frac{2}{r}, \qquad (5)$$

where N_3/τ_{31} is the rate at which N_3 is depopulated to state two and is equal to the rate at which the light source is populating N_3; $\sigma_{13}(\nu)$ is the absorption cross section for the transition from state one to state three and r is the radius of the rod.

If $\Delta N_i(x)$ would reach an equilibrium such that $n_i(il) = n_{i+1}(il + l)$ $i = 0, 1, 2 \ldots$ then one would notice no steady state oscillation. However, since the pump power is limited, with each pass the dominant loss term in Eq. (4), namely, $(1-\rho)n_i(x)$, exceeds the rate at which the pump can replenish the loss, i.e., $dN_2/dt < 0$, and finally $\Delta N \to 0$ and the output power dwindles.

When the transmittance of the filters in Fig. 1 is low, i.e., $\rho \to 0$, or when not enough pump power is used, the spikes terminate when $\Delta N \to 0$, whereas when $\rho \to 1$, the power lost in the filters, i.e., the power going out of the ruby, $(1-\rho)\ h\nu_{12}n_i(x)$, becomes small, so that $\Delta N_i(x)$, though still a function of x, does not change considerably from path to path, i.e.,

$$\int_{il}^{(i+1)l} \Delta N_i(x)dx \simeq \int_{(i+1)l}^{(i+2)l} \Delta N_{i+1}(x)dx \quad i = 0, 1, 2 \ldots . \qquad (6)$$

However, when the Q of the cavity or the pump power is not high enough, the system fails to reach equilibrium and therefore ΔN approaches zero and the spike terminates. There follows a state of inactivity where $dN_2/dt > 0$, and this state lasts until $\Delta N \geqslant C$ before another spike forms. For the above mentioned case, the spacing of the spikes or how often they occur is a function of the pump power; in this case, the output waveform, though of the same frequency, may be spatially incoherent from spike to spike. This could be remedied by increasing the pump power or cooling the system; in either case, more energy is devoted to the central frequency modes in the fluorescence band which overcomes the low Q of the cavity and thus ΔN remains above zero. With more power, the occurrence of the spikes increases and a dc component is added to the pulse. This causes continuity and coherence between the spikes.

Figures 2(a) and 2(b) show a train of pulses in an uncooled ruby laser or represent a cavity with a low Q, while Figs. 2(c) and 2(d) show the output from a ruby laser with high Q such as could be obtained with cooled ruby using highly reflective dielectric coating on both ends.

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Nanosecond Time Response of the Indium Antimonide PEM Infrared Detector

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Response times of infrared photodetectors are presently found to be anywhere between approximately 10^{-3} and 10^{-7} sec. On the other hand, it is obvious that the rise as well as the decay of the signal is determined by the impedance, which may be only partly dependent on R and C of the photosensitive layer itself. In other words, the time response of a specific detector to a large extent may also be determined by its outside configuration, its casing, termination, and connecting leads. The uncooled, single-crystal InSb PEM detector has a low impedance, $Z \sim 20$ ohms; its time constant (decay time of the signal to the $1/e = 36.6\%$ level) is given[1] to be $\tau_d \lesssim 0.4$ μsec.

The *direct* time-response measurement requires a light pulse (preferably rectangular) which is faster in rise and decay than that of the detector; however, light pulses with adequate energy and a halfwidth <0.1 μsec have not been readily available so far. A fast light pulse with a rise time $\sim$40 nanosec was produced by a rotating multimirror system and response times be-

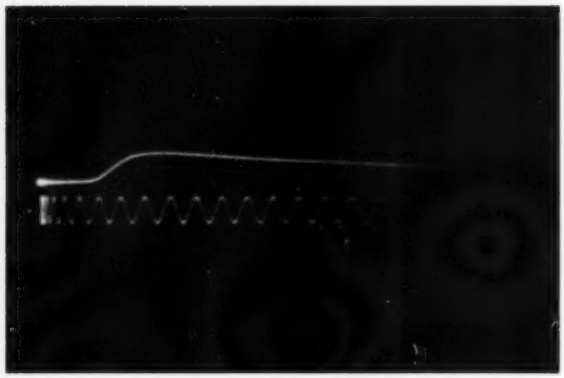

Fig. 1. Rise observed with the indium antimonide PEM detector EG&G oscilloscope, calibration signal 500 Mc.

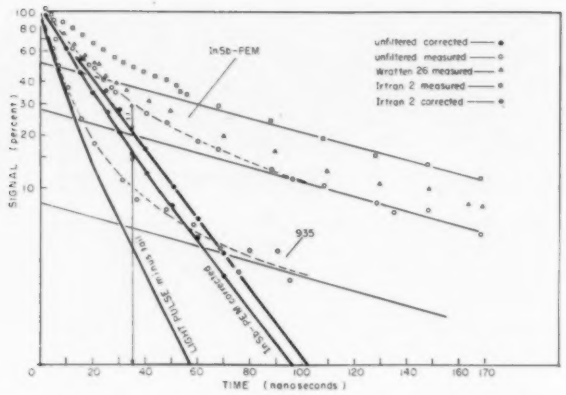

Fig. 2. Time response of the InSb PEM detector compared with the light pulse as observed with the RCA 935. The vertical line represents the difference normalized: $\left[\frac{31-20}{100-28}\right] = 15.3\%$.

tween 16 and 100 nanosec were reported for gold-doped germanium.[2] Recent development of an improved nanosecond spark light source[3] suggested the remeasurement of the published time responses of different photodetectors.

The source used is the SM-4, 465 $\mu\mu$f, gap 1.5 mm, 5.5 kv, half-width ~7 nanosec, peak visual flux ≈ 20,000 candles. The spectrum of this lamp during current maximum is predominantly continuous and the spectral emittance rises strongly from 0.55 to 0.25 μ. The light pulse is focused by means of a Ploetz "clam-shell" mirror system,[4] 15 cm focal length on a Photodetector Model LG 64–InSb PEM, sensitive area 1 × 1 mm, manufactured by Minneapolis-Honeywell. The output is connected to a 51-ohm 12-meter-long delay cable RG-8 and fed directly into an EG&G traveling wave oscilloscope (rise time $r_s \sim 0.3$ nanosec). (Fig. 1.)

The observed 10 to 90% *rise* time is $r_d \gtrsim 2.5$ nanosec against an $r_l \gtrsim 2.0$ nanosec of the light pulse. Hence, the rise of the signal is primarily limited by the detector and *not* by the light pulse; r_d may still be limited by the termination rather than the detecting element.

The *decay* of the photoelectric signal of the InSb is compared in Fig. 2 with the light pulse as observed by means of the ultraviolet sensitive RCA 935 photodiode, S5 response, the latter presenting the true shape of the light pulse between 0.25 and 0.65 μ in the first approximation.

The observed relative decay of the InSb PEM signal is exponential with a slight bend. With ultraviolet and visible light (unfiltered and Wratten 4), the *observed* response time of the InSb PEM to the 36.6% level is $\tau_d' = 29$ nanosec, at which time the radiation (935) has decreased to ~ 11% of its maximum.

An increasingly slower decay is observed by application of spectral filters Wratten 26, transmitting > 0.6 μ and Irtran 2, transmitting > 1.5 μ. Since the infrared is not recorded by the RCA 935, we have no experimental way of checking whether the time response of the InSb PEM detector is slower in the infrared or whether the radiation pulse decreases more slowly. All curves in Fig. 2, including the RCA 935, show the same slope in the tail. This suggests the presence of a light tail. However, such values $\gtrsim 10\%$ gained from scope traces have to be accepted with some caution due to the possibilities of systematic errors such as those resulting from line reflections.

A corrected and truly exponential response of the InSb PEM detector representing the average carrier lifetime is obtained under the assumption that the observed light tail (935) is real. The first step correction subtracts the light tail from the observed InSb curve; these corrected values are normalized as indicated in Fig. 2. The resulting $\tau_d \gtrsim 20$ nanosec agrees roughly with the value determined analytically.[5] The true response time of the InSb PEM detector appears to be smaller; however it cannot be determined accurately because of the too slow decay time of the light pulse.

It must be remembered that the InSb is exposed to high illumination levels producing photocurrents in excess of 10 ma. However, reduction of the incident radiation by a factor > 300, using close to neutral rhodium filters on quartz and raising the signal of the output by a preamplifier (6 nanosec rise), does not change the relative decay curves as presented in Fig. 2; also "linearity" of the amplitudes within this range of radiation levels is observed in the first approximation.

Cornelius C. Gallagher and Peter Tandy performed the experiments; Harold Rose participated in numerous discussions.

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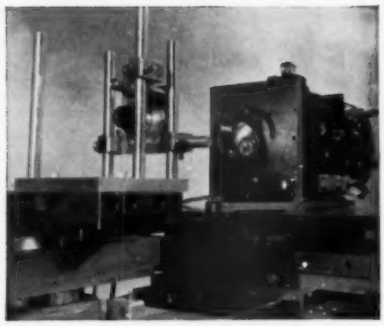
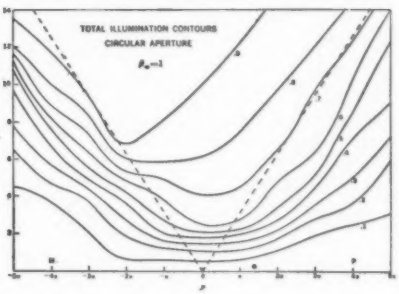
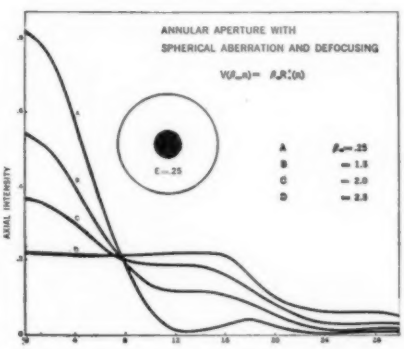
ICO 6 Munich Meeting Information—see page 252



Sine Wave Analyzing Bench



Precision Optical Test Bench



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— SAMUEL JOHNSON

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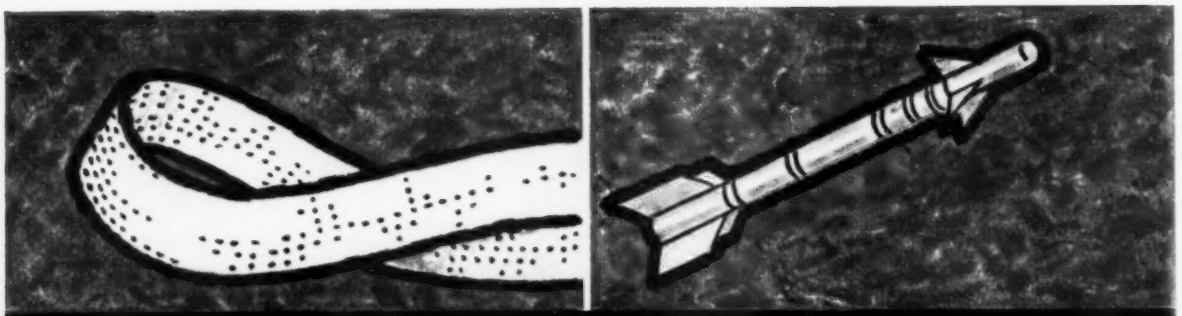
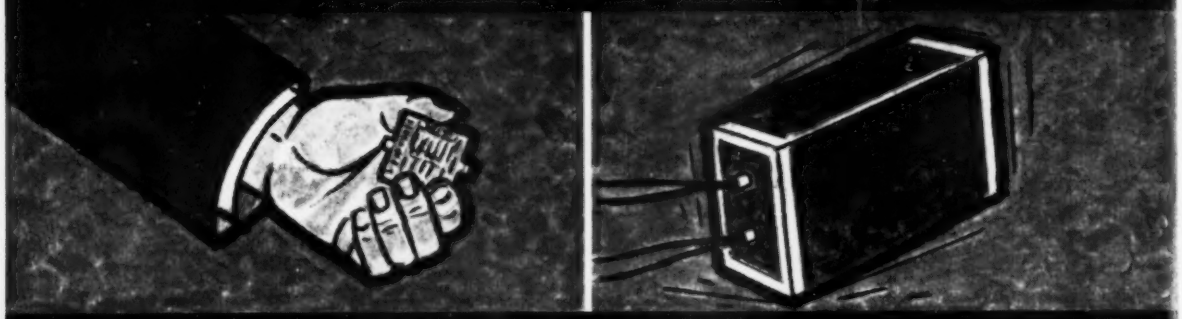


To jog a memory . . . to guide a missile



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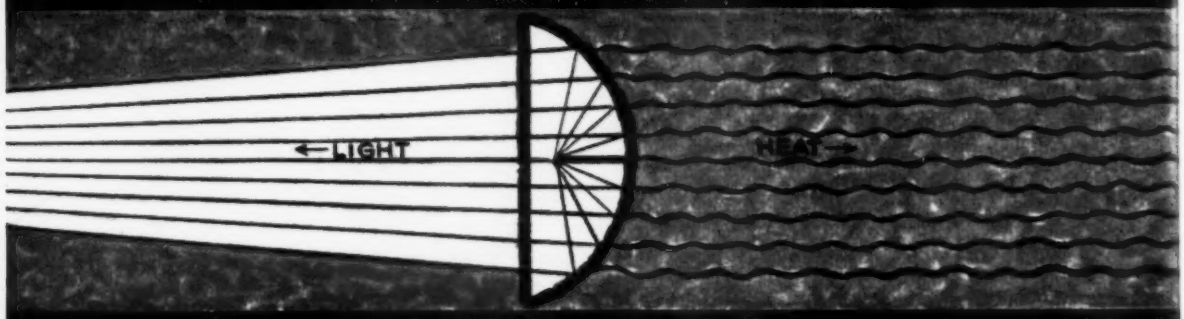

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This photomicrograph is a section through a laser weld specimen made in Mo-1/2% Ti alloy 0.005 inches thick. The weld was made by imaging, at reduced magnification, the end of an experimental AO glass laser on the surface of the specimen. By pulse shaping of the pumping source to control the energy release, the highly localized melting shown was produced without significant vaporization or burning, even though done in air.

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Applied Optics

Optical Activities in Industry

reported by FRANK COOKE, 66 Summer Street, North Brookfield, Mass.
Mr. Cooke welcomes news and comments for this column which should be sent to him at the above address

In this issue let us consider the role of the collimator in measuring angles. In most optical works and many machine shops these measurements are daily necessities.

There is available a variety of excellent tools to facilitate this inspection. Consider Fig. 1. Upon a surface plate is located a precision rotary table and an autocollimator. A polygon has been placed on the table, and on this a precision monitoring square located. Since we are measuring angles neither polygon nor square need be exactly centered. In this instance the polygon is so finely ground and so flat that its surfaces will reflect a sharp image back to the eyepiece. The steel square is accurate to one second and reflects a sharp image. The table is reliable to three seconds.

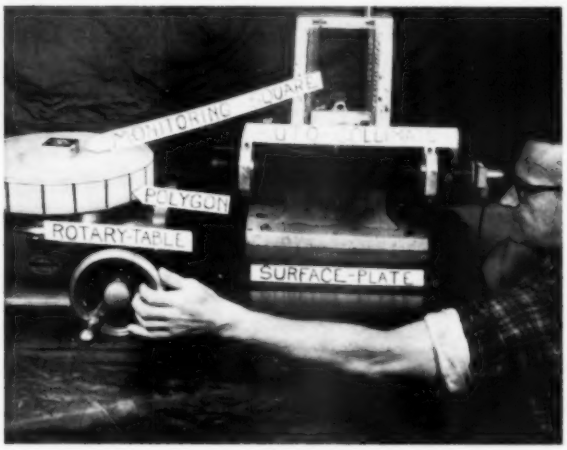

Fig. 1.

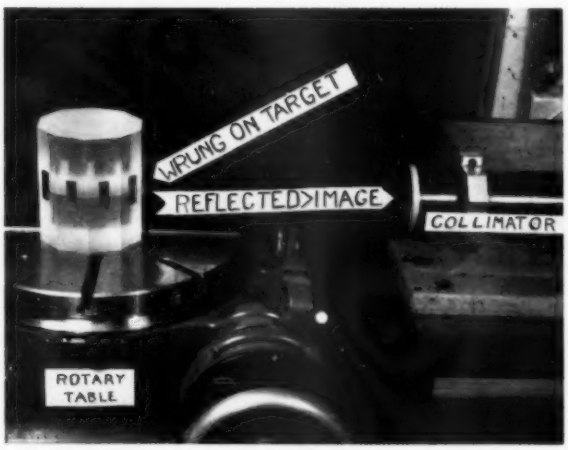

Fig. 2.

By rotating the table and recording when each face reflects back on the hairline of the eyepiece we obtain the polygon's angles. Also, four times in the revolution the monitoring square gives an image. Should the square not be recorded as nearly exactly square we suspect optical gremlins and recheck all readings. It is remarkable how many times this monitoring square technique has helped.

Quite often the shop will have to check polygons so rough that no reflected beam is present. Then standard gage blocks may be wrung on as targets. Figure 2 shows the targets in place on a ten-sided glass film editing prism.

Figure 3 shows targets on a large right-angled prism still mounted in its grinding jig. Experience shows that the wrung on target may add 5 sec to the error.

Fig. 3.

Precision steel angle blocks are shown in Fig. 4. They ring together like gage blocks and are accurate to one second. The polygon rests on an assembly of blocks totaling the angle enclosed by planes A and B. Suppose planes B and B are adjusted manually so that their images in the collimator are the same. By rotating until images from A and A are observed we read the difference. By assuming the steel angle block to be correct this difference is the error of the polygon. Usually this difference is small enough to be read directly in the collimator eyepiece.

An interesting example of how optics helped make an element for Professor John Strong is shown in Fig. 5. Here a very accurate concave surface had to be centered and edged to a rectangular shape and all dimensions held to 0.00025 cm. Figure 6 shows the concave element being held on the end of an accurate cylindrical mandrel through which passes a hole for the admission of vacuum. The edge next to the concave element is an accurate circular knife edge. The element itself is held on the end of this mandrel by vacuum during the centering process. The precision square on the left-hand side enables the operator accurately to rotate the entire assembly in a subsequent sawing and grinding operation.

Figure 7 shows a point source microscope mounted on an old lathe bed so that appropriate movements are provided. The real image from the point source microscope is of course returned by the concave surface. When, upon rotation, this image no longer moves in the field of the microscope, we know the sphere is centered in relation to the center line of the mandrel. This rotation is done by hand and the element moved in the appropriate direction by gentle tapping. The vacuum is admitted through a flexible plastic hose which can twist during the rotation. When no movement of the returned image is observed on several rotations, the back of the concave element is cemented to the steel mandrel using rapid setting cement.

Using this setup the radius of the mirror may also be ascertained. The position of the real image floating in air in front of the microscope objective may be determined. Upon proper focusing, the real image, reflected from the concave surface, is superimposed on this image. Now if an accurate measurement is taken from the center of the element to the front of the objective, and the first-mentioned dimension subtracted, we have the radius of the mirror.

Your reporter has used this method for centering and locating polished steel concave sockets used in the machine tool industry. In these cases the point source microscope was mounted in the foot stock of the grinder.

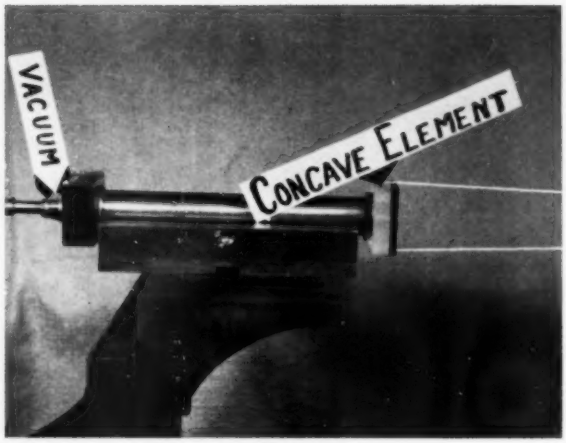

Fig. 6

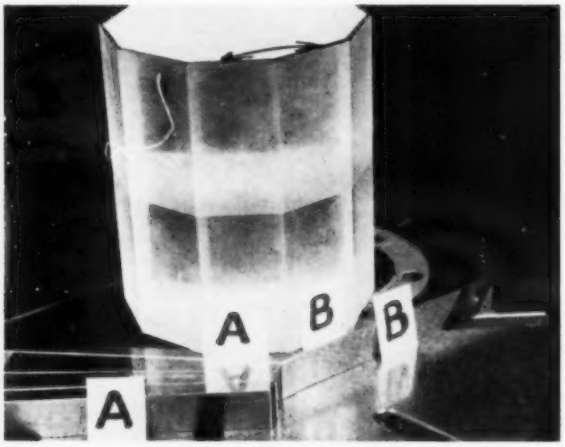

Fig. 4.

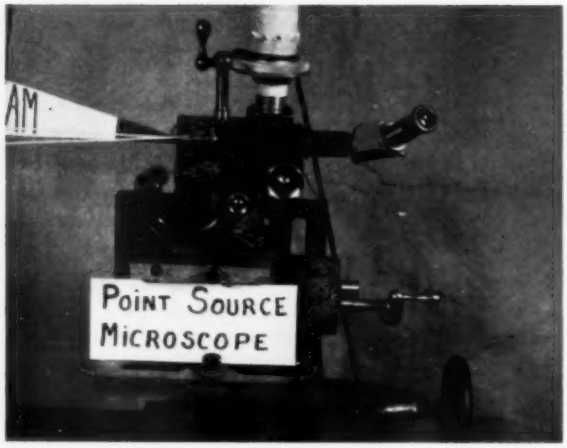

Fig. 7.

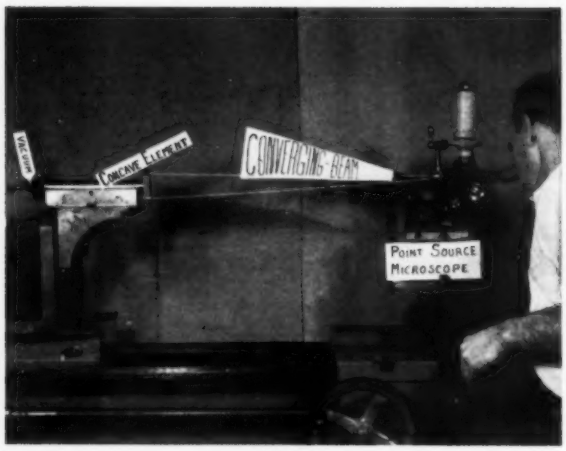

Fig. 5.

photo BEN-ZVI

W. S. Benedict *Johns Hopkins* and John N. Howard *Geophysics Research Directorate* during the Israel Spectral Line August 1961 meeting; *see facing page*

Meeting Reports

Israel International Conference on Spectral Line Shape and Molecular Interactions, Weizmann Institute of Science, August 28–31, 1961

Reported by M. Kent Wilson, Tufts University

Five years have elapsed since a conference has been devoted entirely to a consideration of the shapes of spectral lines and molecular interactions. That the time was propitious for another such conference was made apparent by the attendance of seventy scientists from ten countries at the 1961 conference, sponsored jointly by the Weizmann Institute and the Geophysics Research Directorate, Office of Aerospace Research.

Two-thirds of the thirty papers presented at Rehovoth were primarily theoretical. The main emphasis in the three-day conference was on the pressure-induced shifts of the vibration-rotation lines in the infrared spectra of gases at low pressure, but also included were some papers on pressure effects in microwave spectra of light molecules at low and high pressures, in Raman spectra of light gases at high pressure, and in the ultraviolet spectra of solid noble gases.

Perhaps the most exciting work presented was that of D. H. Rank's group at Pennsylvania State University and J. H. Jaffe's group at the Weizmann Institute, on the dependence upon vibrational and rotational quantum numbers of the frequency shift in self-broadened and foreign-gas-broadened HCl. According to these reports, the shifts in line positions amount to about 0.01 cm^{-1} per atmosphere of pressurizing gas. The magnitude of the shifts and the J-dependence varies from one foreign gas to another and is quite different for inert gases from what it is with polar gases. In both the P- and R-branches the shift is observed to increase with increasing J, and in some cases to flatten out at high J. A second observation is that the dependence upon J is not smooth. Similar measurements on HF with a large number of foreign gases have been made by DeForest F. Smith at Oak Ridge.

The majority of the theoretical papers presented were concerned with this J-dependent frequency shift of rotational lines. Both the "static" model, in which effects due to the time rate of change of intermolecular energy are assumed negligible, and the "collision" model, which attempts to include such effects, were used as bases for theoretical arguments. Perhaps the simplest approach, which could explain several features of the observed shifts and the one that was presented in most detail, was that of A. D. Buckingham of Oxford. In this "static" theory a single atomic neighbor splits the energy levels of the interacting pair into J separate levels which are not resolved because of the variability of the perturbation. The pressure broadening arises through fluctuations in the shift because of its dependence both on the interaction energy and on the values of the quantum number M for the two states involved. This quantum number describes the component of the total angular momentum along the line joining the centers of mass of the two interacting molecules. The frequency shift, which normally lowers frequencies in both the P- and R-branches, is primarily due to the directional properties of the short-range intermolecular forces favoring states in which $M = \pm J$. This circumstance comes about because of the elongated shape of the "molecular complex" formed at the time of collision. Centrifugal distortion effects and effects of the interaction energy on transition probabilities are different for the two branches of rotational lines and predict a turning point in the P-branch. The prediction is qualitatively in agreement with experiment, but experimental observations have not been carried out for high enough J values to provide a definitive test of this theory.

J. H. Van Vleck of Harvard University, in summing up the conference, pointed out that a start had now been made in obtaining molecular constants and, although no theory had yet been developed which would enable quantitative predictions to be made, there was a far greater understanding of the problem. He felt that, in the long run, the "collision" model probably would prove to be more useful than the "static" model.

It was abundantly clear from the papers presented that the field is advancing significantly both experimentally and theoretically. The conference was an unqualified success, both from the scientific and social points of view, and Professor Jaffe and the staff of the Weizmann Institute are to be warmly congratulated.

Seven Days In Israel, September 24–30, 1961

Reported by, V. Twersky, Sylvania EDL

Israel's borders bound cultural activities ranging over thousands of years: there the full spectrum of man's efforts and aspirations exist simultaneously. The scientific activities alone are varied and many-faceted; they are marked by comprehensive and deep programs in many modern fields of research. A brief visit, even one supplemented by reading and discussions with other recent visitors, yields but a few small pieces of the picture. Thus the following fragments are merely illustrative of work at the Weizmann Institute in Rehovoth, the Technion (Israel Institute of Technology) in Haifa, and the Hebrew University in Jerusalem. Since the visits to the laboratories were not prearranged, the account also illustrates the unfailing hospitality I found everywhere in Israel. (Additional material, particularly on non-technical aspects of the trip, will be found in EDL report R497 from which the following notes were abstracted.)

The Weizmann Institute of Science in Rehovoth (near Tel Aviv) is part of Yad Chaim Weizmann, a national memorial area devoted to scientific and cultural activities, commemorating Israel's first President. Founded in 1949, the Institute is the outgrowth of the Daniel Sieff Research Institute built in 1934. It has Departments of Applied Mathematics, Biophysics, Electronics, Experimental Biology, Isotope Research, Nuclear Magnetic Resonance, Nuclear Physics, Organic Chemistry, Polymer Research, and X-ray Crystallography, and also sections for Infrared Spectroscopy, Biochemistry, Photochemistry, Plant Genetics, and Virology and Genetics. In addition the Institute has a Graduate School of Natural Sciences and operates a Ph.D. program in cooperation with the Hebrew University (and to a lesser extent with the Technion and some non-Israel universities). The output of the Institute in quality and quantity is comparable with that of top U.S. science faculties (e.g., 18 students obtained Ph.D.'s during the academic year 1958–9, and 185 papers were published in scientific journals during 1959).

I spent a day with Professor E. H. Frei, Head of the Department of Electronics. The Department's principal activities are in solid state magnetism, acoustics, and medical electronics. Problems in magnetism being studied include the theory of ferromagnetic particles, the effects of crystalline imperfections on ferromagnetism, development of instrumentation for accurate measurements of Curie temperatures, thermocromism (in cooperation with the Department of X-ray Crystallography), and the replacement of oxygen in ferrites by flourine. (In addition, a large number of ferrite materials were synthesized for the Institute's Department of Nuclear Physics and for the Hebrew Uni-

versity, and the Electronics Department also trained the key technical personnel for a ferrite factory in Israel.) In acoustics, a new electroacoustic transducer was conceived and developed, and it is now being applied for use as a loudspeaker, headphone, or microphone. In this transducer, the ordinary paper cone and secondary coil are replaced by a planar membrane on which the coil is impressed as a printed circuit; this membrane is suspended parallel to a planar array of slabs of oriented magnetic material. The vibrating diaphragm of the transducer is driven with essentially constant phase over its whole area, and consequently the speaker has good frequency and transient response. The fact that the new transducer is flat and occupies much less space than conventional cones opens a field of novel applications. In particular, the uses of this principle in stethoscopes, in hearing aids, and for transmitting and receiving very low level signals generated physiologically, are being investigated jointly with members of two hospitals. Other physiologically or medically oriented studies include miniature radio-telemeters to facilitate recording electroencephalograms of animal subjects without interfering with their normal movements (as part of a program on the control of epilepsy). In addition to the fundamental work in physics and electrical engineering being done by the department much fine specialized instrumentation has been developed. Its newest large facility is a modern anechoic chamber.

Dr. J. H. Jaffe, Head of the Section on Infrared Spectroscopy, described their studies on molecular structure and molecular interactions. The principal tool is a large infrared spectrometer-refractometer with many novel features to facilitate very high resolution measurements of gases (the instrument contains a hollow prism gas refractometer of high sensitivity). Simple procedures have been developed for measuring indices of refraction to an accuracy of 1.6×10^{-7}, and differences in the positions of peaks of spectral lines to 0.001 cm^{-1}. The main field of interest centers around the effects of intermolecular forces in broadening a spectral line and in shifting its peak (e.g., an increase in pressure by one atmosphere for a typical gas causes a line shift of almost 0.01 cm^{-1}). In this connection, a systematic survey was made of the spectrum of HCl as perturbed by varying quantities of the inert gases, helium, neon, argon, krypton, and xenon. Their program of precision measurements on resonance line broadening and peak shifts as functions of packing provides fundamental data for dense gas theory, and the theory of intermolecular forces. (Jaffe was recently host to the International Conference on Spectral Line Shape and Molecular Interactions, held in August 1961, and reported on the previous page.)

The Chairman of the Applied Mathematics Department, Professor C. L. Pekeris, is well known for his work on scattering by turbulent media, and for his many fundamental propagation and seismological studies. Their major areas of investigation include computations for atomic spectroscopy, theoretical terrestrial spectroscopy, theoretical seismology, the tides of the oceans, transport phenomena in gases, fluid mechanics, random walk problems, numerical analysis, and electronic computers. The WEIZAC, a high-speed parallel-type electronic computer with a fast ferrite memory, is being used for pulse propagation problems, and for detailed studies of the spectrum lines and fine structure of helium.

The Applied Mathematics Department created and nurtured a geophysics section which carried out an extensive program of measurements. Solutions for pulse propagation in the earth were applied to analyze seismic effects arising from detonated charges and these were exploited to locate oil and water. This section has since become a separate organization—The Geophysical Institute of Israel.

Among practical activities, the Isotopes Department invented an inexpensive technique for producing heavy water and oxygen; this has made Israel a major international supplier of these substances. Various methods for desalting water, for producing synthetic fibers and materials from commercial waste, etc., are also being studied.

The Technion in Haifa, founded in 1912, is Israel's oldest center of higher learning. Its twelve faculties and departments cover modern science and engineering, and its graduates (B.S., M.S., Ph.D.) comprise more than half the practicing engineers of Israel. It has an affiliated Technical High School and a large Extension Program. The older Technion site at Hadar Hacarmel is now used primarily for administrative functions; the new campus is the 300-acre Technion City on Mount Carmel. The Technion has one of the most beautiful campuses in the world (with striking views of the Mediterranean, the slopes of Mount Carmel, and the distant hills), and individual buildings are rapidly being completed for each Department.

Research being carried on at the Technion includes studies on utilization of solar radiation, purification of sea water, hearing aids for the deaf, controlled power production from fusion reactions, cosmic rays, Cherenkov radiation, ionospheric propagation, plasma physics, supersonic flow, and many others.

Professor H. Lindeman (who was Acting Head of the Physics Department in the absence of Professor Rosen) discussed his work in time-correlated radioactive decay processes, and the precision equipment they had developed. Lindeman has made detailed measurements on the distribution of time intervals between successive disintegrations of mesothorium and of other substances. An elegant experimental check-out procedure for the equipment is based on measuring the known distribution of the time intervals for cosmic radiation. Lindeman introduced me to Dr. J. Zak who described his work in theoretical atomic physics, and markedly facilitated my tour of the Technion.

Another of the Laboratories visited, that of Dr. Uri Oppenheim, was carrying out an extensive program of infrared measurements. Oppenheim has developed an elaborate experimental facility to measure radiation characteristics of carbon dioxide (or other gases) as functions of temperature, pressure, and the presence of other gases.

The Technion's cosmic-ray program includes an unusual experimental setup for simultaneous measurements of Cherenkov radiation and cosmic-ray particles. (The best view of the Mediterranean I obtained was from the observatory mounted on top of the Physics Building, to which I had climbed to inspect the counters.) I also visited the x-ray diffraction laboratories, with their facility for preparing samples and growing crystals, and (at the other end of the electromagnetic spectrum) I heard of a vlf program which monitors signals in the 10 to 20 kc/sec range.

In the Electrical Engineering Department, Professor Ollendorff (the present Overseas Vice President of the American IRE) is well known for his contributions to electron optics, for his early diffraction studies, and for recent work on electronic devices for the blind and deaf. The Department has strong programs in electron optics, analog computers, and network theory, special studies in microwaves, acoustics, etc. Dr. Harold Staras of RCA just arrived as a visiting professor; since his specialty is propagation, his interests will link relevant work in both the Physics and Electrical Engineering Departments.

The Chairman of the Mathematics Department, Professor E. Netanyahu (who visited Stanford in 1956, and who is now visiting the Institute of Mathematical Sciences of New York University), is very interested in applied mathematics and this plus the general theme of the Technion encourages a strong effort in analysis related to problems in physics. Their applied studies have included work on schlicht functions, summability methods, differential equations, eigenvalue problems connected with vibrations of inhomogeneous strings and rods, fluid mechanics, and nonlinear oscillations.

The Hebrew University in Jerusalem with over 7300 students

and some 950 teachers (about twice the number at the Technion) is the finest in the Middle East, and one of the finest on the globe. It has complete Faculties of Science, Humanities, Medicine, Law, Agriculture, and Social Sciences; Schools of Education, Dentistry, Pharmacy, Graduate Library Service, and Social Work, and an extensive adult education program. The original Hebrew University buildings, opened in 1925 on Mount Scopus, are guarded by a detachment of Israel's police force cut off from the rest of Israel by territory occupied by Jordan; when access to the buildings on the Mount was no longer possible, the Israelis supplemented this structure by creating a completely new campus (and within five years!) at Givat Ram in Jerusalem. In addition to the recognition received for its scientific, medical, and sociological studies, it has attracted much interest because of its analysis and displays of the Dead Sea Scrolls.

I was shown around the University by Dr. Shaul Yatsiv (who recently spent two years working with Professor Bloch at Stanford). The Physics Department has very strong programs in solid-state physics and in nuclear physics. The solid-state work (under Professor Low) includes various studies on temperature effects in paramagnetic resonance. Yatsiv demonstrated and described their latest equipment, which had been built up to enter the new field of solid-state lasers; the fact that this facility is located within a strong solid-state program gives it a very high potential. The Department also has a strong theoretical and experimental program in atomic spectroscopy, and an exceptional vacuum x-ray spectrograph. One of their best known physicists, the atomic spectral theorist Professor G. Racah, is the Rector of the University, and Head of its Department of Theoretical Physics.

A large variety of additional research programs are in progress at the University, and many of these are carried out in cooperation with other academic, industrial, and military organizations. These include studies on utilization of solar energy, geophysical exploration, nuclear conversion processes, etc.

Many additional centers for research and development exist in Israel than mentioned above: the National Physics Laboratory in Jerusalem is developing special films and containers for "trapping" solar radiation, computer research is carried on in the Scientific Department of the Ministry of Defense, and various high level programs are supported by the Research Council of Israel, Israel's Atomic Energy Commission, and the Israel Institute for Biological Research. A significant amount of research and development is no doubt classified. As for overt military oriented studies, discussion with Col. Y. Lavi, Chief Signal Officer of the Israel Defense Forces (who obtained his degree in Electrical Engineering at Columbia University) indicated a variety of developmental programs (for better batteries, smaller and more reliable equipment, etc.). The "systems problems" of this small country (only twelve miles wide at one portion), practically surrounded by hostile forces, are quite similar to those of field armies under tactical conditions, e.g., problems of interference on microwave communication links, etc. In addition, Israel's Signal Corps has our FCC's responsibility, as well as a direct voice in the operations of Israel's over-all telephone system.

Editor's Note:

Your Editor also spent eight days in Israel while attending the Symposium on Spectral Line Shape and Molecular Interactions just prior to the visit of V. Twersky. We visited primarily the Weizmann Institute at Rehovoth (Professor Jaffe's group) and also the Infrared Laboratory of Uri Oppenheim at the Technion at Haifa and the science laboratories of the Hebrew University at Jerusalem, where Professor Racah was our host. It is perhaps worth mentioning here the vigorous program of exchange of scientific personnel by which such groups as Jaffe's combat scientific isolation. A few years ago Jaffe himself spent two years at Penn State working with Professor Rank. At the time of our visit Professor Jack Goldstein was just returning to Brandeis University after a year at the Weizmann Institute. William Benesch of the University of Pittsburgh has been a Visiting Professor at the Institute for somewhat over a year. Shortly after our visit Dr. Martin Hirshfeld left the Institute to spend a sabbatical year at Tufts University and Dr. Sol Kimel departed for a year at Princeton. Dr. E. K. Plyler of the National Bureau of Standards had just spent several weeks at the Institute and Dr. Aline Landau (of Professor Welsh's department at Toronto) was just beginning a year there. In addition to all this, Jaffe or others of his group manages to attend many of the important international scientific meetings. The group is sufficiently productive that something seems always ripe to present, and at the Symposium on Spectral Line Shape Jaffe's people gave several papers. Their scientific productivity is outdone only by their hospitality, and we were treated to visits to ancient and holy places (Jerusalem, Nazareth, Capernaum, Acre, Caesaria), chamber music concerts in Tel Aviv, and magnificent impromptu beach parties on the Mediterranean.

STOP PRESS

May 23rd - - OSA President MacAdam will address the **Inaugural Meeting of the OSA Washington, D.C. Section,** on *Color In Court.* Georgetown University Faculty Lounge, New South Building 6:30 p.m. cocktails, 7:30 p.m. dinner, 8:30 p.m. lecture. *See also page 385.*

Radiation Commission, I.A.M.A.P., Vienna, Austria, August 14–18, 1961

Reported by J. N. Howard, GRD

During the week of August 14–18, 1961, some 100 delegates from 23 countries participated in a series of meetings sponsored by the Radiation Commission of the International Association of Meteorology and Atmospheric Physics.

The I.A.M.A.P. has several active commissions which meet periodically to consider advances in the state-of-the-art that pertain to meteorology. The two commissions that have the most in common with optics are probably the Ozone Commission and the Radiation Commission. Many of the techniques of measuring ozone in the atmosphere are optical, some based on the ozone ultraviolet absorption between 2900 and 3150 Å and others utilizing the infrared band of ozone at 9.6 μ. The Ozone Commission had met in Arosa, Switzerland, the previous week, and many of these participants had then come to the meeting of the Radiation Commission.

The Radiation Commission meets every two or three years, and sometimes the agenda of the meeting is of rather limited interest. For example, the subject might be the calibration of pyrheliometers, which would attract only the most faithful of meteorologists. This particular meeting however was organized as a series of six symposia of unusual interest, and in addition Vienna in August was chosen as the meeting place. The only factor that kept this meeting from doubling the population of Vienna was

the relative lack of advance publicity and the determination of most of the sponsoring agencies which paid for the travel of the participants to limit the attendees to those actively participating in the meeting by presenting papers or as official representatives.

Symposium I concerned the Radiation Balance and Climates of the Arid Zones, and their Significance in Hydrology and Agriculture. This symposium was organized by the Secretary of the Radiation Commission, G. D. Robinson, of the British Meteorological Office, and consisted of seven papers. The principal paper, "The Radiation Climate of the Arid Zones," was delivered by Dr. M. I. Budyko of the Geophysical Observatory at Leningrad. The Second Symposium concerned Radiative Transfer in a Medium with Scattering and Absorption and was organized by Prof. Z. Sekera of U.C.L.A. This session consisted of twelve papers, mostly theoretical investigations of the scattering and the polarization of solar radiation in the atmosphere, and some papers on cloud reflection and transmission.

Symposium III, Absorption Processes in the Atmosphere, was organized by Prof. R. M. Goody of Harvard, and consisted of a dozen papers all concerned with infrared atmospheric transmission. There were review papers on our present knowledge of the infrared bands of water vapor, carbon dioxide, and ozone (the three principal infrared absorbers), as well as a review of the available data on the trace gases present in the atmosphere. Prof. Migeotte of Liege discussed his program of mapping the infrared solar spectrum from the high altitude observatory at the Jungfraujoch, Switzerland, and Dr. H. A. Gebbie of N.P.L. discussed the application of techniques of interferometry to infrared studies of meteorological interest.

Symposium IV, organized by the President of the Radiation Commission, Prof. Fritz Möller of Munich, concerned the Interaction of Radiation and Fluid Motion, and consisted of seven papers. Here the principal papers were by Prof. Goody of Harvard and Prof. K. Kondratiev of Leningrad.

Symposium V, Thermal Effects in the Upper Atmosphere, was organized by Prof. Kondratiev, who delivered the principal lecture. There were six other papers on radiative transfer processes in the stratosphere.

Symposium VI, Radiation Measurements in the Free Atmosphere, was organized by Dr. Sigmund Fritz of the U.S. Weather Bureau. This session was dominated by NASA-Weather Bureau groups giving preliminary results from the TIROS satellite cloud cover and radiation data, although there were also three American papers on infrared measurements made from high altitude balloons. (One of these, by Murcray, appeared in the March issue of *Applied Optics*.) Kondratiev also gave a paper on actinometry in the free atmosphere.

Almost all of the papers were in English, and the audience was about equally divided between physicists and meteorologists. Prof. Goody, in organizing his session, had written to the participants asking the meteorologists to remember that half of their audience would be spectroscopists, and vice versa, and most of us thought we had prepared our papers with this in mind. Still the chief regrets voiced by some were that the spectroscopists talked for each other, as did the meteorologists.

The meetings were nevertheless fruitful for most of us, as in addition to hearing the above papers summarizing the current status of atmospheric radiation research, we had many opportunities for discussions of research problems with practically every other group active in the field. Vienna in August is not a very musical city, but all of the other attractions are there from Schönbrunn to the Prater to Grinzing, as well as magnificent art museums. Prof. Steinhauser of the Meteorological Institute was our host, and arranged many interesting side tours and visits. In a welcoming address it was pointed out that Vienna has had strong influences on radiation research; it is only necessary to mention Josef Stefan (1835–1893) and Ludwig Boltzmann (1844–1906). Several of us made a pilgrimage to the Central Cemetery to see the Honor Graves of Beethoven, Schubert, Brahms, Wolf, and the Strausses; not far away were the scientists, dominated by the brooding, full-bearded bust of Boltzmann, and on his stone was carved $S = k \log w$.

Fifth International Congress on Ionization Phenomena in Gases, Munich, August 28–September 1, 1961

Reported by E. R. Wooding, University College of Wales

The Congress was organized by the Verband Deutscher Physikalischer Gesellschaften and was held in the Deutsches Museum Munich. Since nearly two hundred and fifty papers were presented in five simultaneous sessions, a report on the conference can only be superficial.

A number of speakers had been invited to review the more important ionization phenomena through the week and the scientific program was opened by A. G. Güntherschulze with a summary of the development of the electric gas discharge.

Many of the investigations reported at this conference were carried out on small devices designed to produce plasmas whose characteristics were controllable and reasonably stable, the simple arc and glow being predominant. Measurements of the *V–I* characteristic of an arc in air have shown that field ionization occurs in the column at currents of less than 0.1 amp. At higher currents the familiar negative characteristic is maintained until electrode material is carried into the column at currents exceeding 100 amp. The characteristic then becomes positive. Arc stability may be improved by a gas vortex, and the effect of temperature gradients may be eliminated by a coaxial flow of gas. H. Maecker reviewed recent progress in arc physics and the development of recent theory.

The study of plasmas in magnetic fields up to several kilogauss has attracted much attention. The diffusion of particles, their concentration, and temperatures under such conditions have been measured. Relations between the discharge current and electron density in a reflex discharge have been determined under pulsed and steady operation. The radiation from an electron beam in a magneto-plasma has been investigated.

Papers on plasma theory dealt with the electric microfield and the Debye-length, transport phenomena, the dispersion of a relativistic plasma, collective processes, rf confinement, and waves in plasmas. H. Grad reviewed the kinetic theory of plasmas with a pleasantly moderate use of mathematics.

Recent developments in spectral techniques applicable down to wavelengths of a few hundred angstroms were reviewed by W. R. S. Garton, who showed a number of new spectra. The spectral range which is of current interest is now very wide: at one extreme, line widths and continua have been examined with an x-ray spectrometer and, at the other, radiation in the range 0.1 to 2 mm has been measured. Radiation from the rare gases and the nature of their continua have been observed in pinches and capillary discharges. The intensity of continua, lines, and their profiles have been studied theoretically and used diagnostically. These techniques were reviewed in detail by H. R. Griem who evaluated their utility in determining particle temperatures. Methods of determining the concentration of neutral atoms in plasmas by the absorption of resonance radiation have been developed.

Many of the radiative processes occur very rapidly so that kinetic spectra with time resolution of a few nanoseconds are of interest. These have yielded information on ionization and decay processes. Other photo-processes on an atomic scale were of interest. L. M. Branscomb discussed the radiative

formation and destruction of gaseous negative ions. The role of photons has been examined in sputtering processes and in a Townsend discharge. In the range 500–1000 Å, the fluorescence of nitrogen, oxygen, and carbon monoxide molecules has been studied.

At microwave frequencies, elegant quasi-optical techniques are rapidly developing. Densities exceeding 10^{14} electrons per cm^3 have been measured with a 2-mm interferometer, and the advantages of a focused beam have been demonstrated. Densities have also been determined by polarimetry and from the variation of group velocity. The electron collision frequency in a plasma has been derived from the absorption of a microwave beam. Electron temperatures have been compared with radiation temperatures measured from the radiated energy. Agreement is good with a dense plasma. The accuracies of microwave, probe, and spectroscopic techniques have been compared in measurements on plasmas having electron densities in the region of 10^{13} per cm^3. Although most investigations have been made in the 8 mm band, descriptions were given of 4 mm, 2 mm, and even 0.76 mm equipment.

Third Australian Spectroscopy Conference, Sydney, August 22–24, 1961

Reported by I. G. Ross, University of Sydney

The Third Australian Spectroscopy Conference was held in Sydney on August 22–24, 1961, and became established as a regular biennial event, supported by the Australian Academy of Science. Australian spectroscopists, somewhat reluctantly reconciled to their remoteness from the main trade routes of science, were heartened by the presence of four overseas participants. It is hoped that these may be the vanguard of a larger international participation at subsequent meetings, of which the next is scheduled for August 1963 at the Australian National University, Canberra.

The 51 papers read at the Sydney meeting spanned most of the electromagnetic spectrum, from the interpretation of the ionization potentials of halogenated alkane radicals (W. C. Price) to an NMR Study of NaSH, the high temperature form of which has a pseudo-NaCl structure due to rotation of SH^- ions (C. K. Coogan and H. S. Gutowsky).

The sessions on analytical applications included several contributions on atomic absorption spectroscopy. The following successful applications were reported: trace quantities of Pb, Hg, Bi, Ni, Cd, Zn in biological materials (J. B. Willis); metals in soils, over a wide concentration range, using a modified Uvispek Spectrophotometer (B. G. Davey); Mo, using an acetylene-air flame to suppress oxide formations (D. J. David); numerous metals in acetylene-air and acetylene-N_2O flames, with special reference to Co and Ni in agricultural materials (J. E. Allan). Cathodic sputtering is being developed as a technique for atomization of elements which form refractory oxides in flames (B. M. Gatehouse, J. V. Sullivan, and A. Walsh).

Representative of other technical developments were: a servo-regulated compulsator for the prevention of image shifts during long exposures in echelle spectrography (G. R. Hercus); continuous analysis of beryllium in air, via the 3130.42 Å line, photoelectrically recorded (L. S. Dale and R. N. Whittem); the study of fluctuations in the rate of electrode evaporation in connection with quantitative emission analysis (J. M. Nobbs); an evaluation of microwave powered Raman sources (N. S. Ham and A. Walsh); and the use of highly monoenergetic electrons (0.05 ev spread) to locate vibrational energy levels of gaseous ions by mass spectrometry (P. Marmet).

In molecular spectroscopy certain themes were discernible. Small molecule spectroscopy included studies of the flames of $CHCl_3$ or CH_2Cl_2 with active N_2 (L. J. Drummond and P. E. Rogasch), and of NH_3 with BrF_3 (C. L. Cook and J. A. Macfarlane); the spectrum of AlO is used to estimate the temperature of re-entering rocket nose cones (J. C. Burns). The following papers reflected the growing interest in the vibronic spectra of molecular crystals: on 9,10-dichloroanthracene (A. V. Bree), on the Davydov splitting in anthracene (A. R. Lacey and L. E. Lyons); on phthalocyanin (M. Batley and L. E. Lyons); and, as part of a comprehensive theory, a relationship was established between the Davydov splitting and the vibrational structure of fluorescence (E. G. McRae). The invidious task of selection from the remaining papers is completed by citing a few papers illustrative of current fields of interest; paramagnetic resonance in the solid system $MnCl_2$-NH_4Cl-H_2O (T. J. Seed); the use of infrared wavelength shifts to determine pK_a values of hydroxy compounds (I. H. Reece and R. L. Werner); the attribution of barriers to internal rotation to an electron-correlation effect (E. A. Magnusson and H. Shull); the determination of transition dipole directions by measuring Kerr constants through absorption bands (A. D. Buckingham).

Report of ISO—TC57 Meeting on Surface Roughness Standards, Moscow, December 12–16, 1961

Reported by E. J. Schneider, Engis

Russian standards in this field are fairly complete and they cover light-section and interferometric instruments, as well as stylus type devices. There is still evidence of Linnik's work, and interferometric comparators are used widely in gage block manufacture. There is an important section on Optics in the All-Union Exhibit of the Achievement of National Economy. This includes a large array of microscopes, telescopes, survey instruments, as well as interferometers of all types, including lens testing, length measuring, and surface finish instruments. The Russian visitor to Moscow, including the technician and the engineer, certainly has an opportunity unparalleled in the West of seeing at all times a complete exhibit of all national products in his field with a chance of gaining some explanation from the attendant of the purpose and design of instruments which he may not yet know.

The December 16th issue of the *Moscow News*, the only English-language newspaper, had an article on modern science Problems headed "A Journey to the Cockles of the Heart" and showed a brand new exhibit which introduced to the Russian public at large the accomplishment of fiber optics. It is typical of Russian translations that they consider the cockles of the heart a place which fiber optics can reach, and this confirms your reporter's experience at the sessions.

The Russian translators frequently have the habit of covering up their ignorance so that at times the sense of a statement may be completely changed by leaving out a "not," or by inserting it when it was not in the original statement. The meetings on the whole were carried on in a friendly and fair spirit, although it was evident that the Russians would not easily permit any change of plans made before the Conference started.

This was one of those occasions when America, Britain, and Canada saw eye-to-eye with the Russians on practically all points, with opposition from the Western countries of the continent—Germany, France, Switzerland, and the Netherlands—who were not all present. This made it rather easy going, although it was useful to have certain elements from the American

Standard inserted in the proposed International Surface Roughness Specification and also to make sure that American instruments will fulfill the proposed standards in the future. I had been of the opinion that Russia on the whole was more optically than electronically minded and, in general, I found this confirmed. Naturally, the electronics which I saw in passing were probably not the latest and certainly not of the miniature or subminiature type which the Russians might use in their own space devices, but, even by American standards of a few years ago, they appear to be rather large and clumsy and, on the whole, not too advanced. I believe that in Russia there is not anything like the feedback from advances made for military or special developments such as space travel, which we find in this country, because apparently normal standard industrial production is much more insulated from special projects than is the case here; this is the reverse side of the Russian tendency of focusing their best talent on those projects which the government wishes to push—it may prove to be one of their great weaknesses in the field of broad technical and scientific advance.

Annual Meeting of the American Physical Society and the American Association of Physics Teachers, New York, January 24–27, 1962

1. A General Review

Reported by Stanley S. Ballard, University of Florida

Do you like your scientific meetings *big?* If you do, let me suggest the combined annual meetings of the American Physical Society and the American Association of Physics Teachers, held each year in New York City late in January or early in February. I attended again this year, and observed that the melee is getting thicker and larger and more vigorous than ever. Specifically, over 4200 physicists registered as well as a couple of hundred students (who pay no registration fee). Of course the chemists and the IRE folk have even larger meetings, but this is the biggest that the physicists have attained as yet, and many of us think it is much too big already.

At the Physical Society meeting alone there were some 41 separate sessions during the three days, most of them of course running in competition with others, with a maximum of seven simultaneous sessions at any one time. In all, 480 papers were scheduled, but there were some postdeadline papers added to bring the total close to 500.

When not attracted by one of the scientific sessions, the registrants could wander through the commercial exhibits and displays which occupied the entire mezzanine floor of the Statler Hilton Hotel. These were twice as extensive as the exhibits at the recent meetings held in the New Yorker Hotel, where much less floor space is available. Many of the college professors spent their time at the publishers' booths, examining books already published, galley or page proofs of books about to be published, and advertisements of books still being written. These are gala days for the scientific book publishers! There were the usual exhibits of laboratory equipment, both for student laboratories and for research use. One friend remarked to me that magnets were in season this year, and in fact there seemed to have been dozens of different magnets on display, of all sizes from the small kit (wind it yourself?) variety to large devices with extensive pole pieces suitable for nuclear resonance research.

The American Association of Physics Teachers operates on a smaller scale, with only two simultaneous sessions in progress at a time. It seems to me that the attendance at AAPT meetings is continually increasing, and some of the invited paper sessions, held in the Georgian Room of the Statler Hilton, attracted capacity audiences of well over 500. The college teachers still talk about their pedagogical matters, but they are also branching out into topics bordering on research—for instance, the excellent three-paper session on low-temperature physics held on Friday morning. One cannot help noticing, after attending AAPT meetings for many years, the slow transition of the audiences from all teachers to teachers plus research men. In fact, several of the papers at this meeting were given by acknowledged leaders among the younger set of vigorous research professors in some of our most distinguished universities.

The session that *everyone* attends is the joint ceremonial session of the two societies, usually held in the tremendous Manhattan Center adjoining the New Yorker Hotel. This year's program was up to the high standards to which we have become accustomed. Frederick Seitz of the University of Illinois gave the retiring presidential address of the APS on the subject "Atomic Defects of Metals." The Oersted Medal of the AAPT, for distinguished teaching, was awarded this year to Professor Francis W. Sears, long at MIT but now at Dartmouth College. Everyone knows the name of Sears, which has appeared on well over a million copies of physics texts—certainly a sales record for any physics professor—but many had not seen him in the flesh until he gave his modest acceptance speech. Finally, Thomas Gold of Cornell University presented the twenty-first Richtmyer Memorial Lecture of the AAPT on the subject "The Arrow of Time."

I will not attempt to give any synopsis whatever of the more than 600 papers given at these joint meetings. I would like to mention, however, one of the postdeadline papers, "A Continuously Operating Ruby Optical Maser," by D. F. Nelson and W. S. Boyle of the Bell Telephone Laboratories. As everyone should know, gas masers have been made to operate continuously, but with solid-state optical masers only intermittent or pulsed operation had been possible. Thus this announcement of a continuously operating ruby laser was of great interest. It employs an unusual optical system to give extremely intense pumping radiation, and the crystal itself is shaped with a conical end ("trumpet-shaped") in order to accept a greater cone of pumping radiation. (Laser enthusiasts have read about this breakthrough in a Letter to the Editor in the March issue of *Applied Optics*. —Ed.)

2. APS Optical Maser Symposium

Reported by Bruce H. Billings and Arthur W. Hornig, Baird-Atomic

On Wednesday morning, January 24, the main ballroom of the Hotel Statler was occupied by part of the program of the annual meeting of the American Physical Society. Some of us in the audience who rarely can sit through a session of this Society, discovered that it was masquerading quite successfully as the Optical Society, and that Physical Society papers on optical masers were indistinguishable from Optical Society papers. A possible exception might be the dispatch with which Chairman Bloembergen of Harvard polished off ten contributed papers, plus one invited paper, so that it was possible to squeeze in two postdeadline papers from Bell Laboratories. The invited paper which was at the end of the program was also from Bell Labs, so that the end of the morning was heavily weighted by the Telephone Company.

J. R. Singer (Berkeley) showed a design for an optical maser which would, perhaps, produce a radiation of narrower bandwidths than existing devices. In the basic equation for maser oscillation bandwidth,

$$\Delta\nu = \frac{4\pi kT(\Delta\nu_A)^2}{P_A},$$

$\Delta\nu$ is the oscillation bandwidth, $\Delta\nu_A$ the bandwidth of the spectrum line being used, and P_A is the power output. In an excited atomic beam, $\Delta\nu_A$ can be very small and, hence, would produce a narrow oscillation bandwidth in a maser configuration. The excited atomic beam would be formed by dissociating an alkali halide, such as RbI, with broad-band ultraviolet light centered about 2537Å. The excited atoms would next enter a Fabry-Perot interferometer and, hopefully, maser action would commence in transitions to ground. Current work is being done on the efficiency of the dissociating process. A problem to be solved is that of achieving sufficient concentration of excited Rb atoms (estimated 10^{16}) in the Fabry-Perot, despite the short lifetime ($\lambda \backsim 10^{-8}$ sec).

L. F. Johnson of Bell Labs then discussed the behavior of optical masers of Nd^{3+} in CaF_2 and $SrMoO_4$. In all these lattices the strongest transition is between the 4 $F_{3/2}$ and 4 $I_{13/2}$ levels, and occurs about 1.06μ. The change imbalance of a trivalent ion in a divalent lattice site can be compensated for by the addition of an alkali metal to the lattice. For 0.190 Nd^{3+} in $SrMoO_4$ at 77°K, with Na present, the threshold for the strongest line has been reduced by about a factor of three, and is 10 joules. In general, the threshold for stimulated emission in $SrMo_4$ is comparable to that in $CaWO_4$, but the threshold in CaF_2 is higher. In an experiment performed with G. D. Boyd, continuous operation for 5 seconds was achieved in the $SrMoO_4$: Nd system using liquid oxygen as a coolant (precooled to liquid nitrogen temperature to eliminate bubbling) and an AH-6 lamp as a pump. The shorter ultraviolet light was filtered with a circulating potassium dichromate solution, and the lamp was run on ac.

W. C. Henneberger changed the mood of the session with a theoretical paper on the origin of optical harmonics. The screen was too full of rapidly shifting complex equations for this reviewer to follow the details. However, the treatment considered harmonic generation as a scattering problem. Certain, general conclusions can be drawn from such an analysis: e.g., double quantum transitions do not occur in spherical, potential distributions, but triple jumps are possible. In other words, frequency doubling will not occur in monatomic gases. These calculations do not apply strictly to maser crystals. During the discussion, Professor Bloembergen interjected that related calculations, extended to include the crystalline case, were being done at Harvard.

The next speaker, D. F. Edwards of Lincoln Laboratory, also spoke on frequency doubling, but used the equation

$$\ddot{x} + \omega_0^2 x + \alpha x^2 = \frac{eE}{m} e^{i\omega t}$$

to describe the behavior of an electron in a system capable of frequency doubling under an applied optical field $Ee^{i\omega t}$. The frequency doubling arises from the nonlinear term αx^2 and the power in the second harmonic is given by

$$P_2 = \frac{2}{3}\frac{e^2}{c^3}\int (\ddot{x})^2 \, d^3p.$$

Carrying through this analysis, it is predicted that frequency doubling should be most efficient in systems where the ratio $\omega/\omega g$ is 0.5, where ω is the pump frequency, 6943Å, and ωg is the frequency associated with the energy gap. A plot of relative intensity versus $\omega/\omega g$ for quartz, sapphire, and ZnS shows that this is indeed the case. A similar analysis for frequency tripling, with a corresponding term, βx^3 in the differential equation, predicts tripling will be most efficient for $\omega/\omega g = 0.33$. Diamond and the alkali iodides are suggested as likely prospects, although no tripling is reported as yet. Symmetry considerations indicate that frequency doubling should not occur in crystals with centers of symmetry; however, radiation should be possible from a surface or an edge. Razor blades turned out to be as effective as KDP, where, with the vector parallel to the edge of the blade, the group obtained one blue photon for 4×10^7 red photons. Terhune, from the Ford Motor Company's Scientific Division, commented that when his group put an electric field on a calcite crystal they got an increase of the intensity of the frequency doubling.

E. S. Dayhoff, N.O.L., presented his high-speed photograph of the emitted light distribution from the end of a ruby optical maser. At 500,000 frames per second it becomes clear that the relaxation oscillations in the particular rubies which he studied tended to emit from different parts of the ruby rod. Considering the apparent extreme variation in mode of oscillation, it seems incredible that observers should find such frequency stability in these oscillations.

P. H. Keck (General Telephone) described a whole series of different geometries for optical maser end illuminating systems which would allow the pumping flux in the material to reach a value which would permit, theoretically, continuous operation of an oscillator. He showed that for some configurations, solar energy should be sufficient to produce such continuous operation in a solid material. It is interesting that in the continuous ruby maser presented in the Bell Labs paper, practically the same geometry was utilized as had been described by Keck.

The Bell Labs paper presented by D. F. Nelson appeared in our March issue. His scheme involves a sapphire-collecting cone at the end of the ruby rod ("trumpet"). The chromium concentration was 1.6×10^{18} atoms per cubic centimeter in the narrow shank, and essentially zero in the cone. A small spot on the face of the cone was made totally reflecting to terminate the oscillating cavity. Using a specially designed, mercury-xenon lamp, the threshold was found to be 850 watts. With a 930-watt input, 4 milliwatts of radiation were obtained with a 0.7° beam divergence. The relaxation oscillations and noise cover a bandwidth from 10^2 to 10^6 cps. The Bell Labs group seemed to feel that the low-frequency components in the 10^2 to 10^3 cps region are vibrations of the ruby. The trumpet geometry seems adaptable to solar pumping, and such experiments are being pursued at Bell.

The third Bell Labs paper, presented by G. D. Boyd, disclosed continuous operation of uranium-doped calcium fluoride. Here, the geometry was similar to that with the $SrMoO_4$ neodymium maser in which liquid oxygen, which had been cooled to liquid nitrogen temperatures to keep it from bubbling, was circulated around the rod. A solution of potassium dichromate to eliminate wavelengths of less than 500 millimicrons was used. The pumping energy in this case lies between 500 and 600 millimicrons. An AH-6 at 60 cycles was used as a source. Relaxation oscillations died out and continuous operation was achieved with the mean emission at 2.56 microns.

The invited paper by W. R. Bennett of Bell Labs was devoted to the helium-neon gas maser. Optimum operating pressures are in the neighborhood of 2 mm He and 0.2 mm Ne; however, it is possible to get maser output with no helium present. The following excitation processes seem to occur:

$$\begin{aligned} \mathrm{He}(2^3S) + \mathrm{Ne} &\rightarrow \mathrm{Ne}(23) + \mathrm{He}, \\ e + \mathrm{Ne} &\rightarrow \mathrm{Ne}(2S) + e, \\ e + \mathrm{Ne}(1S) &\rightarrow \mathrm{Ne}(2P) + e. \end{aligned}$$

The first corresponds to the normal collision excitation of Ne by excited He atoms; the second corresponds to direct excitation of Ne by electrons released in the discharge, and is presumably responsible for maser action when no He is present; the third represents a deleterious excitation which increases the population of the lower maser level. The presence of He seems to increase the

electron density (and, hence, the third process), making pressure control quite critical. A series of experiments was discussed in which two, meter-long helium-neon masers were coupled together in the form of a U. Outputs of each free end could be examined individually and compared, using photomultipliers. Only components polarized parallel to each other can mix at the photocathode. The modes are separated by $c/2\,L$, or 150 mc in this case. The width of a particular line is of the order of 1 mc. Also studied was mode pulling which occurs as the Fabry-Perot is tuned in the vicinity of a very sharp line. The varying dielectric constant actually shifts the Fabry-Perot in such a way that it is tuned more to the line "center" when it is close to the correct frequency. With an increase in power, more and more beats are found corresponding to excitation in weaker modes.

To summarize the session, one can only say that the popularity of optical masers has resulted in extraordinary progress.

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47th Annual Meeting

OPTICAL SOCIETY OF AMERICA

ROCHESTER, NEW YORK
Manger Hotel
October 3, 4, and 5, 1962

In addition to the regular scientific sessions on these dates there will be

***Visits to plants** of great optical interest, October 2nd*

*Trips to **places of general interest**, October 6th*

***Program for ladies**, October 3rd, 4th, and 5th*

Details and registration blanks for these special events will accompany the usual hotel reservation card, Abstract Form, and Preliminary Announcement to be sent to the Society membership. Nonmembers may obtain such information from the Executive Secretary.

Hilda G. Kingslake
Chairman, Program Committee
OSA Rochester 1962 Meeting
56 Westland Avenue
Rochester, N.Y.

Mary E. Warga
Executive Secretary
Optical Society of America
1155 Sixteenth Street N.W.
Washington 6, D.C.

Deadline for receiving abstracts of contributed papers July 16th

continued from page 386

In January Emerson Electric Manufacturing Company of Santa Barbara, Calif., became **Emerson Electric's STAR Division** (Spectral Technology and Acoustic Research). Howard Courtney, formerly of Raytheon, heads the infrared group, and Harry Gilmore, formerly of the University of Michigan has also joined the new group. William F. Riordan is now manager of the STAR Division.... **Xerox Corporation** of Rochester, N.Y., announced recently that it will acquire **University Microfilms, Inc.** of Ann Arbor, Mich. Under the terms of the agreement Xerox will also receive majority interest in University Microfilms Ltd., of England.... Government validation in Japan has been granted to a license agreement between **Rank-Xerox Ltd.,** and **Tokyo Shibaura,** in the field of xeroradiography, the x-ray application of the dry copying process known as xerography. Rank-Xerox is the overseas affiliate of the Xerox Corporation. Principally involved in the development and manufacture of electrical equipment, Tokyo Shibaura is reputedly one of the largest industrial complexes in Japan.... **Aerojet-General Corporation** and the Dutch optical company **N.V. Optische Industrie De Oude Delft** joined forces recently for the development and manufacture of optical and x-ray equipment, and formed the Aerojet Delft Corporation. Headquarters of the new company will be Plainview, New York.

Both **The Perkin-Elmer Corporation** and **Barnes Engineering Company** made vital contributions to Glenn's successful flight. Perkin-Elmer designed and manufactured the viewing periscope of the Mercury capsule. Barnes Engineering developed and is manufacturing the infrared horizon scanners used in the capsule stabilization system. On February 6, 1962, M. M. Merlen, Research Engineer at Barnes Engineering Company, received Patent #3,020,407 on the conical scan horizon scanner principle.... Utilizing a precision optical filter, Glenn observed the shape of the airglow near the Earth's polar regions. This filter, with a multilayer coating only millionths of an inch thick, was made for NASA by **Spectrolab** of North Hollywood, Calif., an associate of Textron Electronics, Inc.

SUPPLEMENT ON OPTICAL PUMPING AND MASERS

An *Applied Optics* **Supplement** on Optical Pumping and Masers will be published in December 1962. This special edition will gather together all the papers in that area of activity published in *Applied Optics* during the first year of publication and include articles not previously published. In addition, a 15,000 word review will be written by O. S. Heavens, *Royal Holloway,* which will not only survey the present state of the art and give fundamental theories but will integrate all the papers published in the **Supplement.** This **Supplement** will be sold at not more than $5.00 a copy.

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Applied Optics

Of Optics and Opticists

This column is compiled partly from information sent by our Reporters in various centers of optics across the continent, but the Managing Editor welcomes news from any source

The Geheimrat in Goethe
Made him all the curter
With Leute who were leery
Of his Color Theory*

David L. MacAdam is now on his Presidential Lecture tour of the local sections. Each section chooses one of two subjects—*Color in Court*, concerning Dr. MacAdam's legal experiences, and *Optical Engineering*, in which he discusses the newest of the professions. He will lecture to the Southern California Section in Los Angeles on May 2, the San Diego branch of Sigma Xi on May 3, continuing on to Dallas where he will install the officers of the new Optical Society of Texas on May 7. (See also p. 379)

A variety of new materials and techniques for laser application is being considered at the **Solid-State Physics Laboratory of the Institute of Science and Technology at the University of Michigan.** Under the direction of **George Makhov,** scientists at the laboratory are: experimenting with uranyl (UO_2^{+++}) compounds which could produce coherent green light; research directed toward the development of a high-power laser and a continuous-wave solid-state laser is being conducted; the possibility of using laser light in a high resolution optical radar system is being studied; and the new technique of placing a right-angle, totally reflecting prism at one end of the laser is being tried. In harmony with this effort, **Peter A. Franken** (of the University of Michigan Physics Department) is working on the generation of the harmonics of the red light from a ruby laser. Under his direction, harmonics of blue light have been successfully developed. (Dr. Franken presented an intensely interesting survey of his work to the OSA-Spring Meeting in Washington, D.C., in March.) Two analysis centers are maintained within the Infrared Laboratory (also part of the University of Michigan's Institute of Science and Technology). In addition to their analytical functions they maintain extensive libraries which serve their respective specialties. The **Infrared Information and Analysis Center** (IRIA) undertakes the collection, analysis, and dissemination of information on infrared research and technology. Under the direction of **William Wolfe,** IRIA publishes regular annotated bibliographies and state-of-the-art reports on such subjects as optical materials in the infrared. The **Ballistic Missile Radiation Analysis Center** (BAMIRAC) undertakes to correlate available data on the radiation emitted from ballistic missiles in all phases of their flight with parameters of the missile and the encountered environment. Under the direction of **George Zissis,** BAMIRAC conducts studies among leading scientists in an effort to derive models capable of describing the observed phenomena. The results of these studies and other research are frequently published in state-of-the-art reports.

A theoretical study by the **Radiophysics Institute of Gor'kii State University** considers the three-level maser as a possible frequency conversion device with noise levels comparable to those of maser amplifiers and with a considerable conversion factor. When the maser responds to two monochromatic signals corresponding to transitions from level E_2 to level E_1 and from level E_3 to level E_2, a combined signal is produced corresponding to the transition from level E_3 to level E_1. This is of practical use, suggest the authors of the paper in the Russian *Journal of Experimental and Theoretical Physics* **41,** no. 3 (9), 986–988 (1961) when one of the initial signals is large. The same effect may be obtained in the optical range, using lasers. Criticism is directed in this paper against A. Clogston for not taking all resonance members of the density matrix into account, and against N. Bloembergen and S. Shapiro for citing Clogston. The Russian authors are V. M. Fayn, Ya. I. Khanin, and E. G. Yashchin, and they also report that a mathematical analysis more rigorous than that used by Schawlow and Townes has been applied to the problem of determining the oscillation conditions of lasers based on cavity or end-plate resonators whose dimensions considerably exceed the wavelength of the generated wave. By this method, a stability analysis is applied to a system of equations of motion describing spin density components. While the analysis is made on the assumption of ideally conducting walls of the resonant cavity, the expression developed for the minimum quantity of active molecules will also be valid for the case of real resonators if the Q-factor of the cavity is much larger than either the total number n of resonator frequency modes or the ratio of cavity dimensions to the wavelength. An example shows that this condition can be fulfilled by devices operating within the optical range; Fabry-Perot interferometers have to be used. Under the assumption that the end plates are 0.5 cm in diameter and are spaced 4 cm apart, the reflection coefficient is 0.95 and frequency is 3×10^{15} cps, the n/Q ratio will equal 0.2.

Design and development of a 9.4-cm solid-state maser for astronomical observations has led **Naval Research Laboratory** scientists to predict improvement by a factor of six in detection signal performance of 15- and 25-meter antennae now in use. The maser bandwidth is about 20 Mc with a gain of 20 decibels, and the equivalent noise temperature of the system should be about 75°K. It is expected that the minimum detectable signal will be about 0.03°K with a 1-sec integration time constant. See NRL Report PB 171 325 by E. McClain, available from the Department of Commerce for $1.25. . . . A literature search of 493 sources on gas and solid-state maser and laser theory, design, and operation is contained in a special bibliography issued by the U.S. Atomic Energy Commission *Masers—A Literature Search* by H. Raleigh of the AEC Division of Technical Information, obtainable from the Department of Commerce for $1.25. . . . OSA hopes to publish an *Applied Optics Supplement* on Optical Pumping and Masers in December 1962; see facing page for more details. . . . A 28-page document entitled "Personalities and organizations active in Soviet maser and laser research" has been compiled from the Soviet technical literature. Listing some 274 publications since 1938, it will be available in early May from the Office of Technical Services, Department of Commerce.

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The **Centre National de la Recherche Scientifique, Paris,** is offering a prize of 10,000 N.F. for the best solution, received before October 1, to the problem of documenting the enormous amount of scientific material at present being published. Further information can be obtained from the Centre National de la Recherche Scientifique, 15 quai Anatole France, Paris 7e, France.

George W. Stroke is taking up the appointment of Professor of Electrical Engineering at the University of Michigan this fall. . . . **Lewis M. Branscomb,** Chief of the Atomic Physics Division of the National Bureau of Standards, has been awarded one of the 1961 Arthur S. Flemming Awards. Dr. Branscomb was cited for his outstanding contributions in the area of the atomic processes of stellar atmospheres, and for his leadership in a scientific program to obtain basic atomic data upon which the successful solution of problems in astrophysics and plasma physics depend. . . . Three other NBS scientists honored are **Earle K. Plyler,** Chief of the Infrared Spectroscopy Section, who received the Department of Commerce's Gold Medal for Exceptional Service. Dr. Plyler was cited for his pioneering advances in the physics of infrared radiation and for major advances in instrumentation for infrared spectroscopy. . . . **Karl G. Kessler** of the NBS Spectroscopy Section was also awarded the Exceptional Service Gold Medal of the Department of Commerce for exceptional originality, scientific achievement, and leadership in the development of atomic beam standards of wavelength. . . . **Wolfgang L. Wiese,** a physicist at the National Bureau of Standards, has received the U.S. Department of Commerce's Silver Medal for Meritorious Service. Dr. Wiese was honored for outstanding research in the field of plasma physics, particularly in the area of atomic transition probabilities. . . . **Francis Scofield** replaces Maj. Gen. C. E. Loucks as Technical Director of the National Paint, Varnish and Lacquer Association on the latter's retirement. . . . At the annual meeting of the Florida Academy of Sciences, held in Tampa in March, two OSA members were chosen to fill posts for the year 1962–63; they are **Alex G. Smith** of the University of Florida, new President-Elect, and **John S. Ross** of Rollins College, new Treasurer. . . . Longtime OSA member **John Sterner,** one of the founders of the firm known nowadays as Baird-Atomic, Inc., now identifies himself with Florida rather than New England. During the hectic period of development of the first intercontinental ballistic missiles, Dr. Sterner served as director of flight test operations of Space Technology Laboratories in the Cape Canaveral area. In 1959 he joined forces with William P. Murphy, Jr., M.D., to form Cordis Corporation, of which he is vice president. This company, located in Miami, performs contract research in the field of cardiovascular medicine with strong emphasis in the area of development of specialized instrumentation. The director of engineering of Cordis Corporation is **Donald E. Williamson,** formerly president of Williamson Development Company in Massachusetts. Dr. Williamson also assists this journal as a member of the newly evolved Patents Panel. . . . **Kenneth G. Macleish,** until recently Assistant Director of Research at Eastman Kodak Company, has joined Perkin-Elmer to become a Vice President and Director of Engineering of its Electro-Optical Division. . . . **John G. Atwood,** formerly Director of Research for Perkin-Elmer's Instrument Division, heads their new department devoted to development and manufacture of optical maser components. . . . The Te Company of Santa Barbara, designer and manufacturer of optical elements, subsystems, and instrumentation, recently announced the appointment of **Harold Fienman** as its representative for New England. . . . Recent appointments at Bausch and Lomb include **Carl A. Day,** Vice-President, and **Leo S. Packer,** Manager of the Space and Defense Division. . . .**Theodore R. Young** has been named chief of the Length Section of the Metrology Division at the National Bureau of Standard, replacing B. J. Page who recently retired after more than forty years with the Bureau. . . The National Academy of Sciences has awarded **Charles H. Townes,** Provost of MIT, its John J. Curty Medal for his pioneering work on masers.

Latest news from the Sections is the founding of the **Optical Society of Texas,** with about 70 founder members. The National Society has been invited to meet there in Spring 1965. . . . The **Southwestern Connecticut Section** has been meeting in the auditorium of the new Stamford Museum Observatory, generally on the last Tuesday of the month. The February talk was on "Recent Developments in Lasers" by A. Yariv of Bell Telephone Laboratories. Earlier talks this season were given by Wallace Brode, William Fastie, W. Lewis Hyde, and Bruce Billings. The March and May meetings feature local talent, viz.: George Derderian and John Ferrara of Sperry Gyroscope's Marine Division on "Daylight Star Detection by Polarization Techniques," and Norman H. Mackworth of Dunlap and Associates on "Experiments With a Camera to Photograph Retinal Images." During a short visit to the United States in April, G. K. J. Garlick, Head of the Physics Department at **Hull University,** England, discussed some of his research in the field of luminescence. Plans are afoot to conclude the OSA Connecticut Section season with a "Conversazione" in June.

The **Institute of the Aerospace Sciences** and the **American Rocket Society** are studying possible consolidation in view of increasing overlapping of areas of interest. So are the **American Institute of Electrical Engineers** and the **Institute of Radio Engineers.** A tentative name for this latter consolidated group is the Institute of Electrical and Electronics Engineers (IEEE). Omission of the word "American" from the name reflects the international interests and scope of the proposed group.

1962 began with an unprecedented upswing in the demand for scientists and engineers, according to the *Engineer/Scientist Demand Index* of Deutsch and Shea, Inc., New York technical manpower consultants. The January figure of 153.7 was the highest so far recorded by the *Index* in the 19 months of its operation. By comparison, the highest *Index* figure for 1961 was 127.3 registered in October, and in January 1961 the Index figure stood at 97.6.

Some recent contracts and grants awarded by the **Office of Aerospace Research** include Univ. of Arkansas, R. H. Hughes *Studies of Optical Polarization by Electron Impact* $25,292; Georgetown Univ., C. L. Beckel *Vibrational Energy Levels of Diatomic Molecules* $24,470; Johns Hopkins Univ., G. H. Dieke *Spectra of Doubly and Triply Ionized Rare Earths* $50,390; Univ. of Utah, F. S. Harris *Interaction of Light with Matter Studied by the Effect of Diffraction on Polarization* $12,332; Yale Univ., R. G. Wheeler *Optical Properties of Insulating Crystals at Low Temperatures* $74,812; Univ. of Oregon, J. C. Kemp *Microwave and Optical Properties of Crystals* $40,419; Univ. of Paris, A. Guinier *X-Ray Scattering by Point Defects* $24,000; Warner and Swasey Co., H. J. Babrov *Infrared Molecular Band Models, Vibration-Rotation Line Widths and Strengths* $25,972; and Hebrew Univ., E. Alexander *Soft X-Ray and Far Ultraviolet Spectroscopy,* $40,780.

continued on page 384

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OSA Group Flight to Europe

AUGUST, 1962

OSA has arranged a group flight with SWISSAIR, for members attending the *Munich ICO Meeting on Image Formation and Vision*, August 20–25. Fare $353 round trip plus $7 organizing fee—$360.

The flight will leave New York (Idlewild) on Monday, 30th July at 6:40 p.m. for *Zurich* by a SWISSAIR DC8 jet, arriving there at 7:05 a.m. 31st July. We shall return from *Munich* Airport on August 27th, at a time to be announced later which will bring us back to Idlewild in the late afternoon of 27th August. Fifty seats have been tentatively reserved and we need your deposits ($50 per seat) **now**; the balance of the charge ($310) must be paid by 30th May.

Members who have already expressed interest have heard from OSA. Others are asked to send in their reservation and deposit at once. This flight is open to members and their immediate families.

* If a minimum of 25 members are interested, it will be possible for members to travel between Zurich and Munich at *no extra* cost. **But participants must travel as a group,** and it is not possible to obtain a rebate on that part of the flight coupon if it is not used. This flight would be on August 19th at about 4 p.m.

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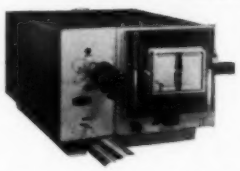

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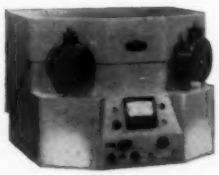

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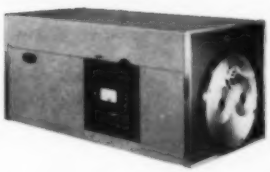

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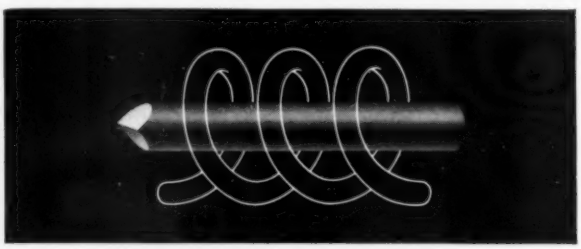

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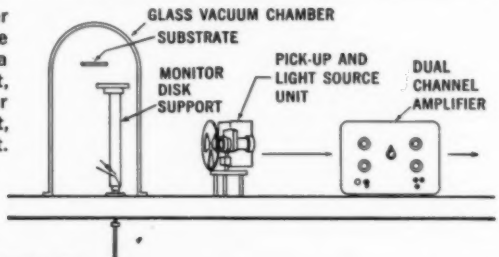

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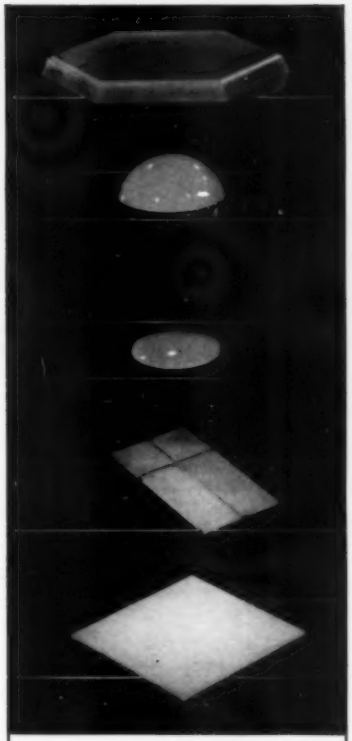

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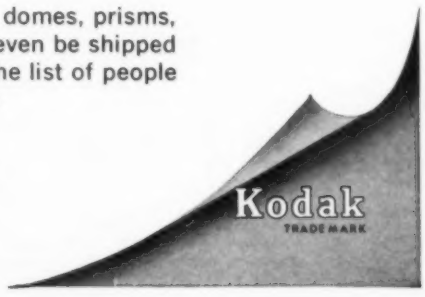
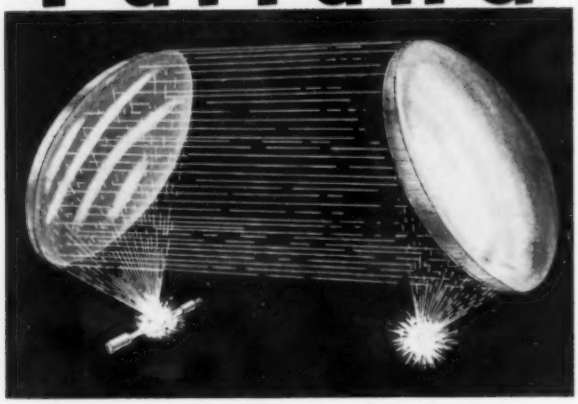


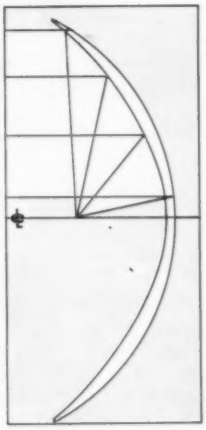
Farrand



Off-Axis Paraboloids

open new possibilities in energy relay systems

This schematic shows how these mirrors are cut from the off-axis area of a paraboloid.



Applications

LASER PUMPING
LIGHT RADAR
DETECTOR OPTICS
COMMUNICATIONS
AND MANY OTHERS

Pairs of Farrand Off-Axis Paraboloids provide highly efficient mirror relay systems in which the two foci are located out of the energy path between the mirrors.

One Off-Axis Paraboloid available from stock has a full 71° acceptance angle and a beam diameter of 7.7 inches. The foci are a full 1¼ inches from the parallel beam. The circle of confusion is .006 inches or less.

Farrand can also supply full paraboloids from 1 to 30 inches in diameter with F ratios from 1.0 to .14. Image errors are normally held to less than .010 inches. Many paraboloids are in stock and delivery on special sizes is usually from 6–8 weeks.

Farrand machines also generate ellipsoids for other relay systems.

Farrand's proprietary optical designs include everything from special eyepieces to special photographic objectives, and many general and special purpose instruments. Send us details of your requirements and let us show you how Farrand can solve your optical problems.

Farrand

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Engineering, research, development, design, and manufacture of precision optics, electronics and scientific instruments.

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Vacuum-Deposited Coatings for Glass, Metal or Plastic

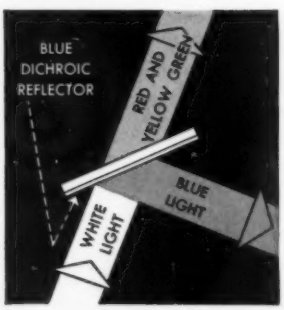
In the field of optics, Liberty Mirror Division of Libbey·Owens·Ford Glass Company has worked extensively for 20 years with laboratory and production technicians here and abroad in the development and application of vacuum-deposited coatings for a wide range of optical and scientific purposes. Three types of these coatings are treated below.

Front-surface mirrors give perfect reflection without double images.

Recommended for optical, scientific and commercial uses where a single reflection of high perfection is desired. Back-surface mirrors reflect a second image from the front surface of the glass.

The opaque, reflective aluminum deposit is coated with hard quartz to increase durability. These mirrors can be made to withstand temperatures well in excess of 200° F. They resist moisture and salt atmosphere far better than chemically silvered mirrors. Can be readily cleaned by any normal, non-abrasive glass cleaning procedure.

Dichroic reflectors put light and heat to work, your way.

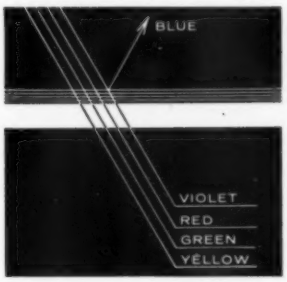


What do you want to do with a light beam? In millimicrons, what wave lengths do you want reflected? Where do you want spectrophotometric reflection to peak?

Liberty Mirror offers a standard line of dichroic coatings that reflect 90% or more of incident light in wave lengths from as low as 400 millimicrons up to 800 millimicrons. If a Hi-Efficiency dichroic coating hasn't already been pinpointed to meet your specifications, Liberty Mirror will go to work on one.

Multiple coatings deliver wave lengths, to order.

These coatings, applied in separate layers to glass or plastic, allow you to split light beams in many ways on a single application. Multilayer coatings can be applied to produce a specific beam-splitting result.



Liberty Mirror engineers can do all the design and development work on any potential use for this technique, or help solve application problems.

★ ★ ★

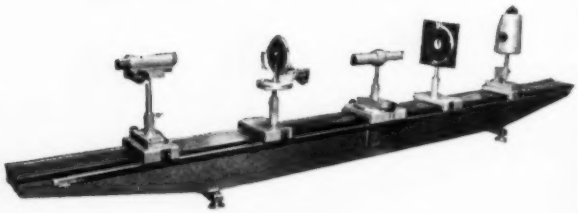
Among the coatings available from Liberty Mirror are aluminum, chrome and gold front-surface mirrors, neutral filters, transparent mirrors, high-efficiency beam splitters, beam-splitting dichroic mirrors and filters. Metallic and transparent electrically conducting coatings are available for resistance heating. Static-dissipating and high-frequency shielding coatings are also available.

Liberty Mirror can apply coatings to all types of glass, plastics, epoxy material and highly polished metals.

Vacuum-deposited coatings are used in such varied products as scientific and optical instruments, cameras, aircraft and missiles. Free data sheets are available on all coatings. Write L·O·F, Liberty Mirror Division, 5552 Libbey·Owens·Ford Building, Toledo 2, Ohio.

WHAT'S NEW!

THIS MAGNIFICENT CREATURE . . .



. . . is our $990. Precision Lathe Bed Bench.

R & J Beck have lavished on this $990. bench the love befitting a fine instrument. There are four reasons this bench makes sense.

First, *Quality:* It is cast in stress-free Meehanite, 2.1 meters long. It weighs over 125 pounds.

Second, *Precision:* It is guaranteed accurate to $2^1/_2$ thou over its entire length in both plan and elevation. Who else guarantees a bench under $1000?

Third, *Detail:* Slides are of dovetail cross-section for high precision.

Fourth, *Versatility:* (We're nearing the cat's meow; read slowly.) The precision carriers accept all 50-plus accessories now widely used with our triangular "Zeiss" form benches. And, at $2^1/_2$ thou precision, the accuracy of this bench is such that with a special carrier, it is both reasonable and possible to use the accessories designed for our higher priced Research Benches.

Now consider:

This bench is *at once* the Prefect to a line of benches and accessories starting as low as $12.90 and Pageboy to the magnificent Research Benches. As one's investment in accessories is typically twice that of the bench, it is comforting in this age of ferment in optics to discover a Bench such as this with precision and capabilities in reserve! Rather like the cat's meow, don't you think? **May we send you our Optical Bench Brochure?**

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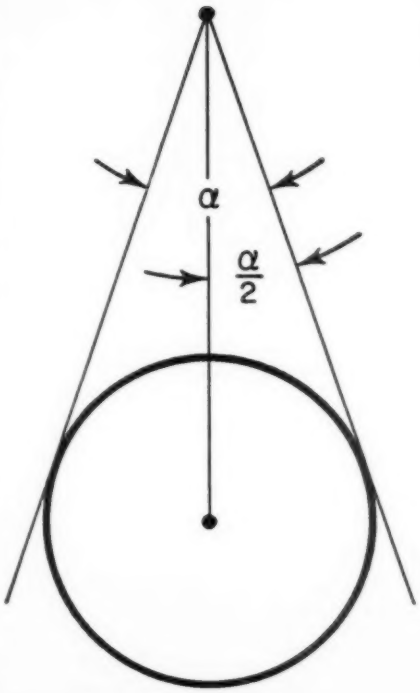

ge·o·me·try

Greek **geo·metrein,** from **ge,** earth; **metrein,** to measure

PROBLEM: (Euclid, ca. 300 BC): From a point outside a circle, using only straight edge and dividers, construct a line through the center of that circle.

SOLUTION: (Barnes Engineering Company, 1962 AD): By means of an **infrared straight edge,** the two tangents from the point to the circle are constructed, giving the subtended angle α. By means of **electro-optical dividers,** the angle α is bisected. The bisector is the required line. QED.

COROLLARY: If the point is a space vehicle and the circle is a plane through the earth, the bisector is the local vertical in that plane.

One elegantly simple method of implementing the above solution is Barnes Engineering Company's conical scanner*. This and other types of infrared horizon sensors developed by Barnes' engineers and scientists are being used for space vehicle control and stabilization over both the day and night zones of a planet.

Barnes Engineering is actively engaged in solving vital problems such as these for the U. S. Government. We need scientists and engineers with creative imaginations to help us in our expanding space instrumentation program, on projects such as: navigation and stabilization sensors for space vehicles (MERCURY, AGENA, MARINER); meteorological instrumentation for weather satellites (TIROS); pre-launch alignment equipment for missile guidance systems (POLARIS); and trackers and radiometers for re-entry measurements (DAMP).

At Barnes Engineering, you will have the opportunity of working with people who have been designing space instrumentation since before the first satellite launching. If you can contribute to the solution of interesting and important problems in infrared and electro-optics, please write or call collect for a confidential interview:

Mr. Edward R. Tarczali, Personnel Manager

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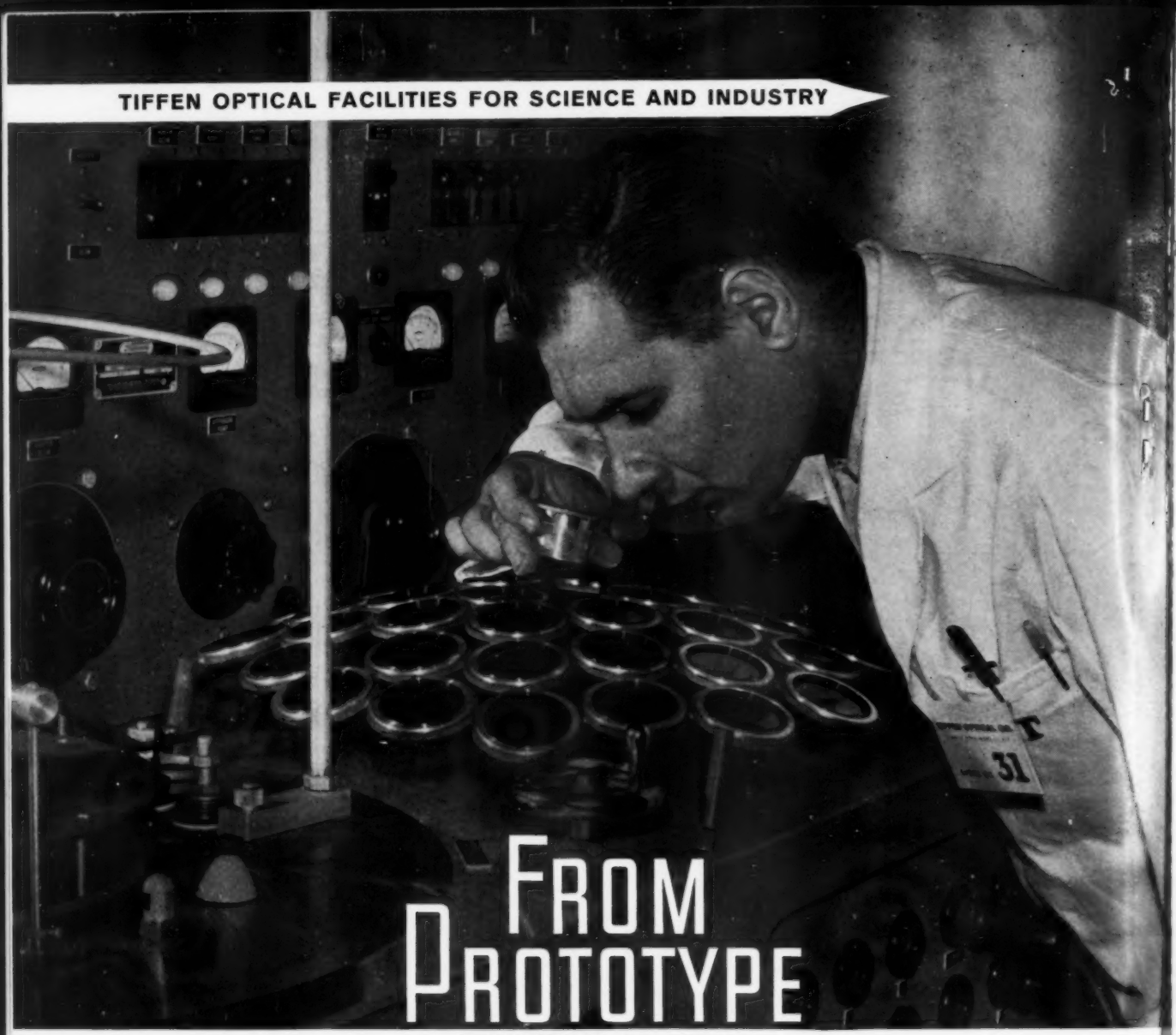
*Patent No. 3,020,407

TIFFEN OPTICAL FACILITIES FOR SCIENCE AND INDUSTRY



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A unique integration of prototype and production facilities . . . that is TIFFEN! For over a decade, government agencies, leading industrial firms and photographic studios have turned to TIFFEN for precision photographic optical accessories.

Now, TIFFEN offers their specialized experience and greatly expanded facilities to all industry employing optics in their product. TIFFEN's major facilities are described below, and are constantly being augmented to conquer specialized problems.

BLANCHARDS ... flat grinding to .00005". Diamond grinding wheels for shaping to .0001" tolerances. Sizes to 18" dia. ***EDGING*** . . . glass and ceramics, to tolerances less than .001", up to 20" dia. Precision bevels and odd shapes ground. ***DRILLING*** . . . dia. from .010" to 12", concentric to within .0005", on glass, ceramics, silicon, germanium, etc. ***GRINDING & POLISHING*** . . . from subminiature optics 1mm dia. to mirrors 24" dia., to within 1/10 wavelength in flatness, less than 2 seconds of arc in parallel. Roof prisms to 2 seconds of accuracy. ***COATING*** . . . high vacuum deposition of all types of material. Hot and cold magnesium fluoride coating, partial coatings for beam splitters and metallic neutral density filters. Aluminizing, with silicon monoxide overcoat, for high reflection mirrors. A battery of 22" bell-jars, temperature and humidity controlled dept. ***COLOR LABORATORY*** . . . includes Densichron, Beckman Du Spectrophotometer, Weston Foot Lambert Meter, environmental test equipment, etc. ***FILTERS*** . . . laminated glass equal in environmental tests to solid glass, with superior color control. All colors and curves, .040 to 12" dia., thickness .025" to 1", resolution to 100 lines per mm. ***MACHINING*** . . . multi-spindle automatics to 4", secondary machines to 10" capacity. Thread cutting, Whitworth, English and metric, with single point tools. High precision lens barrels and metallic optical parts. ***TOOL ROOM*** . . . modern 23" swing lathes, grinders, millers. All tools and jigs manufactured internally.

Special problems? Write, call or visit: **TIFFEN OPTICAL CO.**, 86 Jane St., Roslyn Hgts., L. I., N. Y. West Coast Rep.: CRAIG CORP., 3410 So. La Cienega Blvd., Los Angeles 16, Cal.

TIFFEN DELIVERS THE GOODS!

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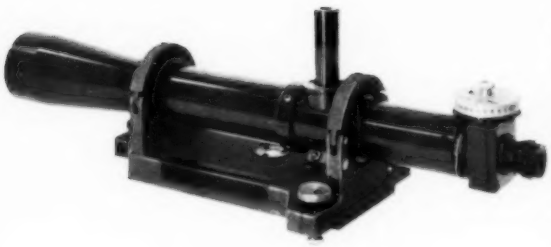

Visual Auto-Collimator

- Aperture 50 mm.
- Equivalent focal length 900 mm.
- Range 10 minutes
- Graduations to .1 second
- Working distance 0-50 ft.
- Magnification 53.5X
- Field of view 22 minutes
- Exit pupil 1 mm.

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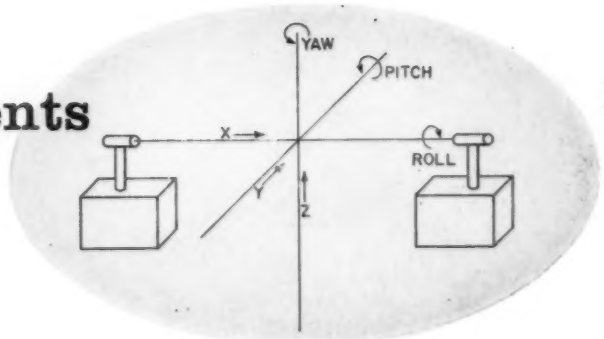
Two Axis, Fast Response, Electronic Auto-Collimator

- Indicating range ±125 seconds of arc
- Operating distance 0 to 5 ft.
- Linearity 2% at 5 feet distance
- Response time 25 milliseconds
- Noise 500 milliarc seconds max.

for any of these requirements



- Displacement – X, Y or Z
- Angular deviation – pitch, roll or yaw

Look to K&E for the precise visual or electro-optical equipment needed to measure, monitor, record and control the relative attitudes – in twist or displacement – of any body in relation to another. The O&M Division's capabilities also include precise distance measurement, goniometry and optical spatial-coordinate measuring systems. Write today for technical information and facilities brochure.

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- Photoconductive Cells
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- Spectrographs
- Spectrometers
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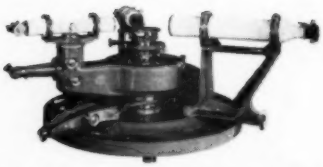
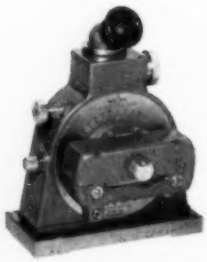
- Thermopiles
- X-ray Equipment

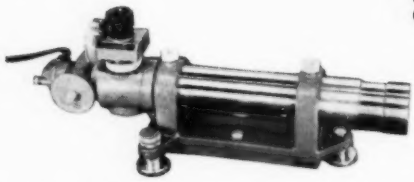


SPECTROMETER C-20 For research refractometry and highest class goniometric work. Refractive index measurement to sixth decimal can be obtained; micrometer scale divided at 0.1 second intervals.

MONOCHROMATOR D-290 Small, compact, low cost; utilizes a 15,000 lines/in. plane grating with special range of 2000A to 10,000A and dispersion of 70A/mm. Easily combines with other optical systems.



PRECISION CLINOMETER TB-95 Reads angles and circular spacing direct to 1 second; by estimation to 0.5 second—through 360°. Accessories permit use in horizontal position as rotary table or dividing head for light work.



UNIVERSAL AUTO-COLLIMATOR TA-51 The master instrument for angle measurement. Reads in both planes simultaneously. Range 10 minutes of arc; direct reading to 0.1 second; straight or right angle viewing.

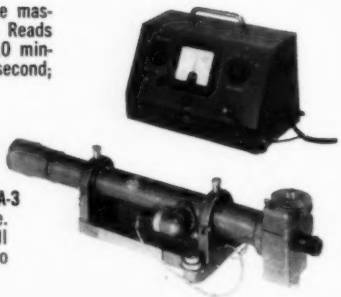


PHOTO-ELECTRIC AUTO-COLLIMATOR TA-3 Eliminates human factor — fatigue. Adjustable sensitivity and range; full visual optics. Setting accuracy to 0.05 second.

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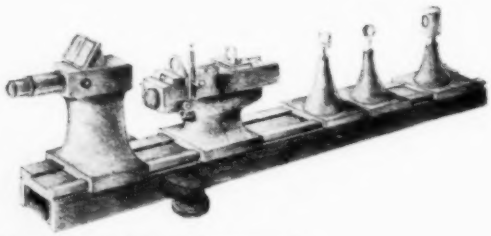
HILGER PRECISION OPTICAL BENCH Massive Meehanite casting holds heavy instruments with no flexing; supported at three points for precise levelling. Flat ways are hard chrome plated for long life; absolutely rust proof. Designed for convenient, universal mounting of accessories.



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